Kymenlaakson ammattikorkeakoulu
University of Applied Sciences

Jouni-Juhani Häkkinen
Svenja Baer, Hanna Ricklefs

Economic comparison of three NO_x emission abatement systems.

Kymenlaakson ammattikorkeakoulu
University of Applied Sciences
2013

No: 99
ISSN: 1239-9094

Research and Reports
Series B

ECONOMIC COMPARISON OF THREE NO_X EMISSION ABATEMENT SYSTEMS.

Jouni-Juhani Häkkinen
Svenja Baer, Hanna Ricklefs

Kotka, Finland 2013

Publications of Kymenlaakso University of Applied Sciences.
Series B Research and Reports. No: 99

Part-financed by the European Union
(European Regional Development Fund)

Publisher: Kymenlaakso University of Applied Sciences
Printing press: Kopijyvä Oy, Kouvola 2013
ISBN (PB.): 978-952-5963-88-5
ISBN (PDF): 978-952-5963-89-2
ISSN: 1239-9094
ISSN: (e-version) 1797-5972

FOREWORD

This document is a study report for BSR InnoShip, the Baltic Sea co-operation establishment for reducing ship and port emissions using knowledge and innovation-based competitiveness.

BSR InnoShip addresses the common challenge of countries on the Baltic Sea and key maritime stakeholders to cooperate in minimising ship-based air pollution, while aiming to optimise the competitiveness of the maritime industry. The project will promote an innovative transnational approach to harmonising the various needs and interests of the maritime sector and to ensuring a level playing field for more sustainable and economically viable management of the Baltic Sea's resources. The project will provide the knowledge and best practices that policy- and decision-makers need to develop and implement national and transnational policies, strategies and concrete measures to implement international low-emission requirements. Practical models and tools will be elaborated to estimate the economic implications of the required emission reductions and encourage voluntary measures and economic incentives for low-emission solutions locally, nationally and in the Baltic Sea area as a whole.

Kymenlaakso University of Applied Sciences contributes to BSR InnoShip by offering high-level competence in marine emission measurement activities. The emission measurement laboratory of Kymenlaakso University of Applied Sciences was established in1992. The laboratory has taken part in several significant international projects and has completed measurements on over one hundred vessels. The emission measurement laboratory of Kymenlaakso University of Applied Sciences is accredited by FINAS according to the SFS-EN ISO/IEC 17025:2005 standard.

BSR InnoShip

ABSTRACT

This report summarises the nitrogen oxides (NO_x) emission abatement studies conducted at Kymenlaakso University of Applied Sciences for the BSR InnoShip project. Some of the results have already been published in Clean shipping currents vol 1, number 7. (ISSN 2242-9794).

The results presented here are based on the on-board NO_x measurement campaign involving nine ships between 2011 and 2013. The NO_x emission levels of various engine types with three different types of NO_x emission abatement technologies were studied. The measurements were taken on board during the normal operation of the vessels.

The report briefly describes the technologies being studied and presents calculations and comparison of the NO_x emission abatement levels achieved. The cost of purchasing and operating abatement equipment is calculated. The abatement level is projected against the costs of the technology in each case. The conclusion combines the final results in a simple figure of euros per ton of NO_x emissions avoided for each vessel and technology studied.

The purpose of this document is to serve as an informative report. As such, any recommendations or grading of the abatement technologies are outside the scope of this report.

ACKNOWLEDGEMENTS

This paper in based on the work of a research group comprising several researchers and students. The authors of this report would like to thank all the people who contributed to this work.

This report is dedicated to the memory of Risto Korhonen (1951 – 2013).

Symbols and abbreviations

g	Gram
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt hour
m	Metre
m^3	Cubic metre
ppm	Parts per million
s	Second
°C	Degree celsius
%	Per cent
€	Euro
BSR	Baltic Sea Region
CAC	Charge Air Cooler
Capex	Capital Expenditure
CASS	Combustion Air Saturation System
CO	Carbon monoxide
CO2	Carbon dioxide
DWI	Direct Water Injection
ECA	Emission Control Area
FINAS	Finnish Accreditation Service
HAM	Humid Air Motor
i.e.	that is
IMO	International Maritime Organization
MARPOL	Marine Pollution
ME	Main Engine
NH3	Ammonia
NO	Nitrogen monoxide
NOx	Nitrogen oxides
O	Oxygen
SAM	Scavenge Air Moistening
SCR	Selective Catalytic Reduction
SO2	Sulphur dioxide
STID	Steam Injected Diesel Engine
TBO	Time Between Overhaul

Contents

1 INTRODUCTION

This report presents three case studies of common NO_x abatement technologies. The purpose of the study was to measure and compare the cost-efficiency of the selected technologies. This report aims to provide information on real-life situations and it relies heavily on the results of actual measurements. The economy aspects of the selected cases are established by considering each vessel individually. Conclusions are therefore mainly bound to the case vessels; however, some of the information can be generalised.

The case studies are based on measurement periods aboard ships and interviews with technical staff and management personnel involved in the ships' daily operations. Relevant information was also provided by technology suppliers. The measurements were made according to the ISO 8178–2 standard and Annex VI to MARPOL 73/78 (IMO NO_x code) or equivalent standards. This report presents various measurement results and observations related to the subject. The complete measurement reports are available on request.

Several publications and literary resources were consulted to find reliable base values for the calculation of the cost-effectiveness of the abatement technologies. Furthermore, brochures and product data sheets from the engine manufacturers provided necessary information. Experts from the engine industry, equipment manufacturers and shipping companies were consulted. In most of the cases, exact price information from manufacturers of the technologies could not be disclosed for business reasons.

11

2 OVERVIEW OF THE THREE ABATEMENT TECHNOLOGIES STUDIED

The three emission abatement technologies studied here are among the most common abatement technologies. The technologies were selected for this study because they were considered to provide high abatement efficiency. The technologies are briefly presented below. A more detailed presentation can be found in the corresponding chapter later in this document.

Selective catalytic reaction

The SCR process uses a chemical reaction and a catalytic reactor to reduce NO_x. The chemical agent (urea) is introduced to exhaust gas and the mixture is channelled to the reaction chamber. The reaction is accelerated with a catalytic material and the result is water and nitrogen gas. The technology is widely used both in land-based power plants and marine applications for NO_x reduction.

Humidification of charge air

The charge air humidification method is based on lowering the combustion temperature by introducing water to the combustion process. The water is in vaporised form and it is mixed to the charge air. In the context of this report the humidification technology is referred to as HAM. This is an abbreviation of Humid Air Motor, which is the commercial brand of marine engine manufacturer MAN Diesel. This technology has a limited number of reference installations.

Injecting water into the combustion process

The water injection method uses liquid water, which is injected as a spray to the combustion chamber. The manufacturer of the study subject system is Wärtsilä. Wärtsilä has renamed the technology brand to Wetpac, but the former abbreviation, DWI, was chosen for this report. This technology has dozens of reference installations.

The two water-based technologies, HAM and DWI, operate on the principle of preventing NO_x formation, whereas the SCR technology operates as an after treatment of the exhaust gas.

3 SELECTIVE CATALYTIC REACTION (SCR)

There are two common catalytic methods for reducing NOx. These are selective (SCR) and non-selective catalytic reaction (NSCR). The non-selective catalytic reaction process includes several other reactants beside NOx. The SCR system addresses only NOx compounds through the selective reaction. The marine applications are SCR systems.

3.1 Operating principle of the selective catalytic reaction

Selective catalytic reaction is essentially a chemical reduction reaction between ammonia and nitrogen oxides accelerated with a catalyst. The catalyst reactor, or the catalyst bed, is usually vanadium-titanium or a platinum-based alloy and zeolite. SCR converts NO_x into nitrogen and water.

In a typical SCR system, the reduction agent (s solution of urea and pure water) is sprayed into the exhaust gas. The mixture passes through a reaction chamber, and a reaction takes place in the presence of a catalyst at high temperature. Ammonia forms from urea. Urea is used instead of ammonia because it is easier to handle and store. The complete reaction is as follows:

$$CO(NH_3)_2 + 2\ NO + ½\ O_2 \rightarrow 2\ N_2 + 2CO_2 + 2\ H_2$$

The reaction produces non-toxic gaseous components, nitrogen, water vapour and carbon dioxide.

The sulphur content of the fuel affects the catalyst reaction. A high sulphur content in fuel can reduce the efficiency of the SCR system significantly. A sulphur content below one per cent is considered harmless in this regard.

The catalytic system is mechanically quite simple. It consists of a urea tank, pipelines, nozzles, fluid pumps, an air compressor, a reactor casing, cleaning devices (soot blowing) and a control unit. A schematic diagram of a generic installation is presented in Figure 1.

13

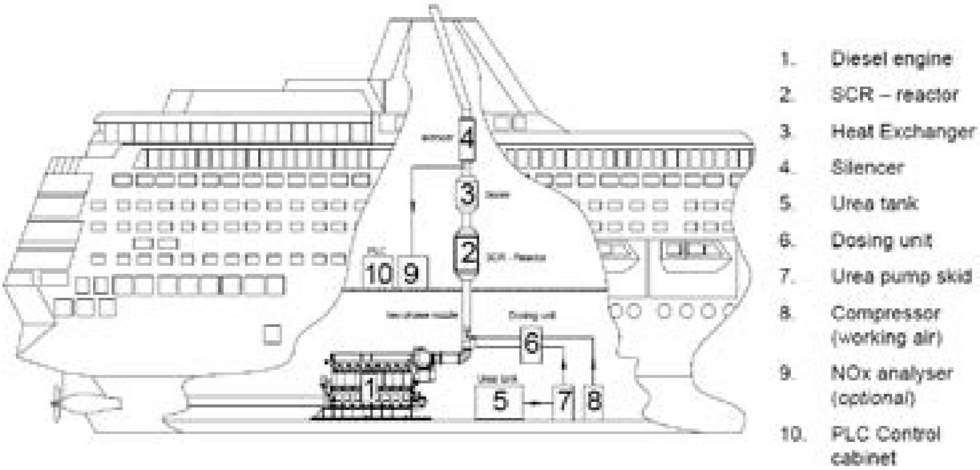

Figure 1. Schematic diagram of a SCR system.

The disadvantage of the SCR is the requirement of installation space. The system occupies quite a lot of space, and retrofitting a SCR system is not always possible due the lack of the room for the reactor case. Some manufacturers offer systems where the reactor case can replace the silencer.

The dimensioning of the reactor depends on the engine and the volume of the exhaust gas flow. Typical dimensions of a SCR reactor case are 4 x 2 x 2 metres for a 7 000 kW engine. The weight of a single reactor of this size is approximately 6 tons. One reactor is needed for each engine. For example, reactors for a ship with four engines require a total of 64 cubic meters of installation space (total of four reactors not including the pipelines and other auxiliary equipment). Reactors can be cased individually or combined, depending on the configuration of the exhaust gas channel layout.

The SCR system does not affect the power of the engine. There is no need to modify the engine (internally or externally) or replace engine components to apply a SCR system.

3.2 Reduction level references in literature

The reduction level of NO_x can be very high. Reduction levels of over 90 per cent are reported and some manufacturers claim even higher percentages. The reaction requires temperatures of 300 to 500 ^{o}C, and this is the main limitation in the operation of a SCR system. The combustion gas does not always reach high enough temperatures, especially when the system is running under reduced load.

The reduction level depends on several variables and environmental conditions:

- The catalytic reactor wears with time, affecting the efficiency of the reaction.

- Varying concentrations and temperatures of exhaust gas affect abatement efficiency.

- 'Ammonia slip' – the amount of the ammonia in the exhaust gas after the reaction – is also one of the factors in evaluating the abatement system. The excess of ammonia results in toxic and corrosive exhaust gas and higher consumptions of expensive reagents.

The control unit of the SCR system has some internal latency for changes in environmental conditions, and this can reduce the overall efficiency of the SCR system, especially in variable load manoeuvring.

3.3 Measurements aboard the case study vessel

The measured vessel is a passenger ferry (ROPAX) operating on a short route with frequent port visits. The planned vessel run time was 365 days in the year of measurement.

The vessel has main engines of type Wärtsilä 16V32LN with a nominal power of 6560 kW. The engines are turbo-charged 4-stroke diesel engines, non-reversible with charge air cooler and direct fuel injection. Two of the four main engines were measured. The total number of operating hours of the measured engines was roughly 30 000 each.

The measurement situation reflected a typical running situation. The typical engine load at sea was 85 per cent. Typically, two of the four engines were running depending on the weather conditions. However, it was not unusual for the vessel to run using three or four engines. Port maneuvering periods were quite short.

4 OVERVIEW OF THE COST OF USING SCR

4.1 Purchase price

Commissioning a SCR system includes system design and installation. Available pricing information indicates a fairly uniform pricing level between different manufacturers. The case study vessel has a SCR system installed as new.

Retrofit system pricing was also discussed, although this information has no direct link to the case study vessel. Retrofitting the system can be difficult and it can even require the exhaust gas channel structures to be rebuilt. The retrofit purchase price was estimated to be 25 – 35 per cent higher due to the greater amount of design work necessary. The available space within the ship and the need for disassembling the ship structures sets the price spread (which can be very wide) for installation expenses. The cost of dockyard days and lost operating revenue can also vary. This can result in a very high installation cost for a retrofitted system. These factors must be calculated for each individual ship.

Both new fit and retrofitted SCR systems are tailor-made and designed according to the engine specifications of the ship.

4.2 System installation costs

The general cost of installing a SCR unit is very difficult to estimate, even in coarse figures. SCR unit installation and installation-related ship construction work includes work input from several contractors.

The shipping company did not have any available information on the installation cost. The supplier of the system for the case study vessel was also unable to calculate the installation cost figures in exact numbers, due to the involvement of multiple contractors. The best available information was a general estimate that the installation and dockyard costs are roughly the same as the purchase price. Accordingly, the installation price is obtained by multiplying the purchase price by a factor of two. This figure is naturally rather indeterminate, but it is based on and supported by an experienced system supplier. A similar rule of thumb was also used by another system supplier.

The system installation cost, calculated with the assumptions specified above, is € 360 000.

4.3 SCR system lifespan and renewal

The lifespan of a catalytic reactor depends on the equipment usage. A rough estimate of the lifespan is 10 to 15 years. In this report the lifespan is set at 12 years.

4.4 Summary of the capital costs

Total purchase and installation price estimates for the case study vessel were € 720 000. Annualised costs with a 12 year lifespan are € 60 000 (excluding financing costs).

4.5 Operating costs

Operating and maintaining the SCR system gives rise to costs that are minor in comparison with the overall cost. The system supplier and the vessel's technical personnel provided the cost estimates below, and only general cost ranges were discussed.

4.6 Personnel costs, operating and maintenance

The SCR system's mechanical parts require maintenance, in the same way as any other machinery. Everyday maintenance can be carried out by normal ship crew and no specialist work is required. Routine cleaning and inspection does not significantly add to costs. A comprehensive inspection is performed along with the manufacturer at defined intervals. The cost of inspection is not public information. For the purpose of this report, the operating and maintenance costs are estimated to be € 5000 per year.

The SCR system is controlled by an automatic unit and does not require personnel to operate it. The control cabinet is located in the control room of the vessel. Control system malfunctions are rare.

4.7 Replacement parts

The system wears over time and some parts must be replaced. The urea nozzles are particularly prone to wearing. Nozzles are quite expensive and therefore the shipping company has started a service program for nozzle maintenance in order to extend the nozzle lifetime. Nozzle costs are approximately € 5000 per year.

Catalyst elements wear down and they must be replaced when the catalytic efficiency decreases. The elements can be replaced individually. The cost of replacement elements is between five and ten thousand euros per year. The case study vessel is quite new and catalyst elements have performed well so far, but it is obvious that replacements are needed more frequently as the system gets older. Annualised costs for element replacement during over the SCR system's lifespan are estimated to be € 8000.

Replacing other parts (pumps, etc.) does not significantly add to annual costs. However, occasional breakages can cause unscheduled costs. For the purposes of these calculations, these costs are estimated at € 2000 per year.

4.8 Consumables

The SCR system uses water and urea. A high-concentration urea solution is diluted with fresh water and the final solution is approximately 40 per cent urea. Urea and water are bunkered in port.

The bunker price of high-concentration urea is about € 300 per ton. Urea is diluted with fresh water, which also has a certain cost. However, this cost is insignificant compared to the cost of urea and, therefore, the price of fresh water was omitted from our calculations. Fluctuations in the price of urea tend to roughly follow the price of fossil fuels.

Data in the measured ships' consumption records was examined and a period of eight days was sampled to calculate the average urea and fuel consumption. Source information and a summary of the results are presented in Appendix 10.

Based on the fuel energy content analysis and engine-specific fuel consumption, the urea consumption was 17.5 g/kWh (see Appendix 10., table A10-2). The reference value, obtained from literature and the SCR system supplier, states that the urea consumption is normally in the range of 15–20 g/kWh. The calculated value is therefore well inside the range.

Urea consumption for one year based on the values above is 1500 m^3 (1670 tons) and the cost is € 500 000.

For comparison purposes, the urea consumption was calculated against the oil consumption and the urea/oil ratio was 7 per cent (70 litres of urea per cubic metre of oil).

4.9 Total cost and conclusion

The total cost calculation is based on the abovementioned figures, which are believed to be accurate. A summary is given in Table 1. Estimates are made using the best available background information. Nevertheless, this type of calculation includes some uncertainties by default.

Table 1. Total cost of operating SCR.

	Annual cost
System design, purchase and installation expenses	€ 60 000
Operating costs	€ 20 000
Consumables	€ 500 000
Total	€ 580 000
Total with ± 10 % uncertainty	€ 520 000 – € 640 000

This calculation reveals that the most significant cost of operating a SCR system is the consumables, effectively urea.

5 NO_X EMISSION ABATEMENT ACHIEVED WITH SCR

The NO_x emission abatement achieved with SCR system is derived from two separate measurement runs. These measurement runs were carried out in 2011 and 2012. The measurement run in 2012 is considered as the main source of the abatement calculation data for this document and the 2011 measurement results were used for reference purposes.

5.1 Measurement results and review

A summary of the measurement results is presented in Table 2. An excerpt from the measurement report is presented in Appendix 1.

Table 2. NO_x reduction levels with SCR.

	Average	The figures adjacent are calculated by averaging two measurement results. The calculation is presented in Appendix 1.
NO_x before SCR	10.35 g/kWh	
NO_x after SCR	2.65 g/kWh	
NO_x reduction	7.7 g/kWh	
Uncertainty ± 10 %	6.9 – 8.5 g/kWh	
Reduction percentage	74 %	

These measurement results strongly indicate that the reduction level is lower than expected.

Reduction reference values from a previous measurement run by the same vessel are significantly higher. The reason for the difference is suggested to be the performance fluctuation of the SCR system. This situation indicates the integral uncertainty and complexity of both the general methodology of the long-term abatement calculations and assessment of abatement technology.

5.2 Amount of NO_x reduction

The summary calculation of NO_x reduction is shown in Table 3.

Table 3. Mass of NO_x reduced.

Annual main engine energy usage	95 000 MWh
Reduction amount	7.7 kg / MWh
Abatement in one year	730 tons
Uncertainty ± 10 %	660 – 800 tons

Calculated from the average load rate of the vessel, the total energy generated by four main engines in one year amounts to 95 000 MWh. Energy consumption calculations are presented in Appendix 5.

Using this figure and the reduction level from Table 3., the NOx abatement for one year is 720 tons (uncertainty 70 tons).

6 COST CALCULATION OF NO_X ABATEMENT ACHIEVED WITH SCR SYSTEM

The calculation of costs and emission abatement levels is summarised in Table 4.

Table 4. Price calculation per avoided ton.

Average annual cost of running SCR	€ 520 000 – € 640 000
Abated NOx emissions	660 – 800 tons
Price per abated ton	€ 800
Uncertainty ± 15 %	€ 660 – € 900

7 SUMMARY OF SCR SYSTEM STUDY

The measured vessel was equipped with four Wärtsilä 16V32LN main engines. The typical engine load at sea is 85 per cent with two engines running simultaneously. The overall average engine load including sea run and port manoeuvring is 72 per cent. The vessel operates continuously all year under different ambient conditions.

The measured vessel has a newly installed SCR system. The SCR system has been measured several times, and the level of measured abatement varies considerably. The measured values indicate that the reduction values given by the manufacturer can be achieved under optimal conditions. During normal operation, optimal performance cannot always be achieved, resulting in inconsistent abatement level. This can be considered to be characteristic of SCR in marine operations.

The cost calculation gives an estimate of the cost of operating a new installation of SCR equipment. The overall annual cost is around € 600 000. The cost of the reduced NO_x is in the neighbourhood of € 800 per ton.

The cost of urea accounts for a large proportion of the total cost. Because of this, the market price of urea plays a significant role in the economy of a SCR system.

8 DIRECT WATER INJECTION (DWI)

One of the water-based methods of abating NO_x emissions is direct water injection (DWI). DWI uses water to lower the temperature during combustion. As the name indicates, water is introduced to the process by direct injection into the cylinders of the engine.

The case study ship has DWI technology from Wärtsilä installed. It operates with water injection preceding 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 to note is 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 decreased duration of gas mixture in the combustion chamber.
The DWI system does not require chemical agents or bunkered consumables.

8.1 Operating principle of the water injection system

The burning process is cooled by injection of water directly into the cylinders of the engine. The cooler burning temperature prevents the formation of thermic NO_x. There are several different injection approaches: injection through separate injectors, one for fuel and one for water; through separate nozzles in one injector; or stratified injection.

The type of DWI injection used in the case study vessel is called tandem or combined nozzle. This system is marketed by Wärtsilä under the name 'tandem nozzle'. A descriptive picture of the construction is shown in Figure 2.

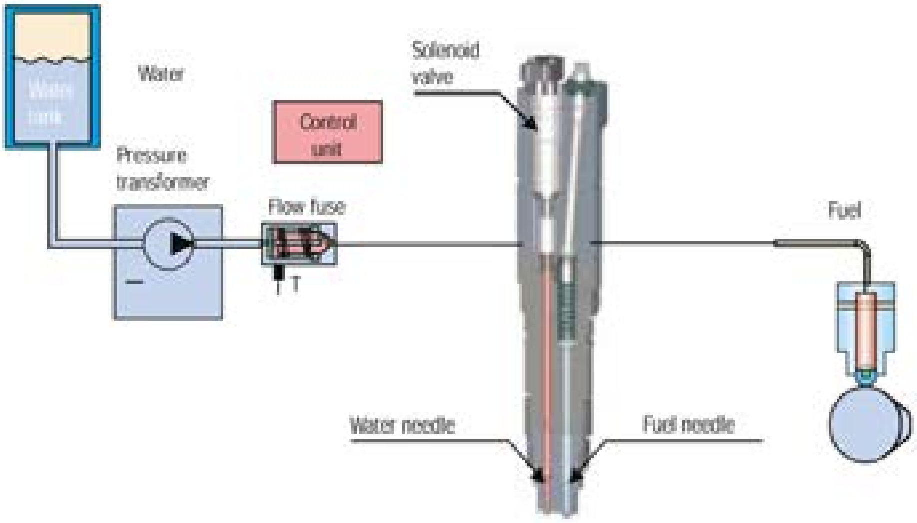

Figure 2. Construction of a tandem nozzle

The name implies the method, because the supply of water and fuel occur separately, 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 its own computer-controlled unit to optimise the injection parameters. It is possible to change the amount of water added according to the conditions of the engine. For example, during start-up or while operating under low loads, water injection can be reduced or shut off completely.

Injection types are differentiated by the nozzles used and also by the water pressure used. Stratified water injection does not need high water pressure, while injection using twin nozzles requires a pressure of 200 to 400 bars, depending on the type of engine. This system is assembled with a high-pressure water pump module. Additionally a low-pressure pump has to be installed before the high-pressure pump, providing a constant 3.5 bars of pressure to guarantee stable water flow between them.

One advantage of the combined nozzle is that higher rates of NO_x reduction (compared to completely separate nozzles) can be achieved with no influence on engine operation. The engine can operate with water injection on or off due to the separate feed pipes. For marine engines, reliable and failsafe operation is very important, owing to the fact that the entire ship will not manoeuvrable if the fuel supply collapses and the engine stops. In the event of an error in the DWI system, such as 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.

To achieve a NOx reduction of 50 – 60 per cent, a water to fuel ratio (W/F ratio) of 40 – 70 per cent is necessary. If more water is fed into the combustion chamber it is possible to reduce NOx emissions further, but this also involves a reduction in engine efficiency.

The operation of a DWI system includes considerations of fuel consumption, the power of the engine and the amount and composition of emissions in the exhaust gas. To reach a balance between these different attributes the key parameters need to be considered carefully. These encompass injection timing, including the duration of water injection and the direction of water spray.

8.2 Water production

As a further requirement, the installed DWI system needs fresh water. This means drinking water or even distilled water is required to prevent damage to the engine. Other types of water may cause the engine to clog due to impurities. An advantage for cruise ships is the possibility to use drainage water from showers, which can be used after preparation. The water injected into the cylinder must be free of solids, so it needs to be filtered. Furthermore, if a water treatment system is installed, seawater can be used. After filtration the water needs to be desalinated to prevent hot corrosion. If there are too many salts, such as sodium, they may come into contact with the sulphur in the fuel, or other substances such as vanadium, form a layer on the surface of the cylinder and pit the cylinder at high temperatures.

Regardless of the effort required to filter and desalinate the water, it is beneficial that wastewater or seawater can be used. Otherwise, huge tanks would be necessary for the storage of fresh water on the vessel. These additional tanks would mean extra weight and loss of space. The case study ship had a water treatment system installed, which is capable of producing high quality fresh water from seawater.

Water consumption is related to fuel consumption, and this relation can be shown as the water/fuel ratio (W/F ratio). The W/F ration of the case study ship was calculated at 0.64. This ratio represents a situation in which 0.64 m3 of water is consumed per cubic metre of fuel consumption. The typical range of water to fuel is 0.4 – 0.7.

8.3 Special features of the system

The case study ship's personnel suspected that the water injection nozzles were malfunctioning. This suspicion proved well founded when the measurement results were analysed. The NO_x emissions were at the same level with three or four nozzles operating. This finding may indicate a broken nozzle, which lowers the efficiency of NO_x abatement. The emission levels measured with a malfunctioning system have been used in this report, as the purpose of the case study is to reflect the actual situation instead of the optimal conditions. See Appendix 8. for graphs of the situation described above.

8.4 Reduction level references

Wärtsilä has reported a 50-per-cent NO_x reduction level with DWI. A reference value of 60 per cent has been reported from measurements of a DWI-equipped ship conducted in 2011 by Kymenlaakso University of Applied Sciences.

9 OVERVIEW OF THE COSTS OF USING WATER INJECTION

The following price information is gathered from several literary sources. The engine manufacturer and the shipping company were also consulted.

9.1 Purchase costs

The purchase and installation costs include the costs of equipment and installation work. The equipment includes a humidifier, a catch tank and a heat exchanger for preheating the water. Further components include pumps, filters, pipes and valves, as well as the control and monitoring system. The advantage of the system is that the most expensive components, such as the humidifier, the heat exchanger, the catch tank and the circulation pump, must be bought only once. It is not necessary to install these devices for each engine. To enable comparability, the lifespan of the three options is assumed to be 25 years.

Based on various sources, a purchase cost of € 40 per kW was used for the calculations in this case study. Greatly varying values are to be found, even from the manufacturer of the DWI system, Wärtsilä. Statements often begin at € 10 – € 15 per kW and range up to € 40 – € 60 per kW.

Additional DWI components, such as a low-pressure pump (3.5 bar) and a high-pressure pump (200 – 400 bar), also need to be installed. As mentioned earlier, further parts include injection valves and a flow fuse. Both have to be built into each cylinder, along with cables, pipelines and the control unit for each cylinder. The total cost is approximately € 300 000 and the installation has a lifespan of 25 years. This includes the purchase costs of the water treatment system.

The injector required has a relatively short lifespan of four years. This is due to the exposed position of the injectors in the cylinder, where it has to endure high pressures and temperatures. An injector price of € 66 000 was used for this study.

The cost figures are presented and annualised in Tables 5. and 6.

Table 5. Purchase costs of DWI equipment (one engine).

General equipment, life span 25 years	€ 300 000
Injectors, life span 4 years	€ 66 000

Table 6. Annualised costs of DWI equipment (not including capital costs).

General equipment, life span 25 years	€ 12 000 per annum
Injectors, life span 4 years	€ 16 500 per annum
Total	€ 28 500 per annum

9.2 System installation costs

System installation costs are confidential by agreements between shipping companies and equipment manufacturers. At the time of this study, the DWI equipment manufacturer, Wärtsilä, did not offer retrofit installations.

9.3 Operating and maintenance costs

The operating costs of this system include the costs of fresh water. The case study ship had 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. The ship's staff estimate the cost of this to be € 2000 annually.

A further factor that needs to be considered is 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. This generates extra workload for the ship's personnel. The cost of the extra annual workload is approximated at € 2000.

The operating costs are collected in Tables 7. and 8.

Table 7. Annual operating costs.

Fuel for water generation	€ 2 000 per annum
Maintenance work	€2 000 per annum
Total	€4 000 per annum

9.4 Total cost and conclusion

The annual cost of the DWI system installed is presented in table 8. The cost structure presented above reveals that a single item – the injectors – constitutes half of the costs.

Table 8. Total cost of operating DWI.

	Annual cost
Equipment	€ 28 500
Operating and maintenance	€ 4 000
Total	€ 32 500
Total with ± 10 % uncertainty	€ 29 000 – € 35 500

The calculation above is for one engine. The case study ship has two main engines, and the total annual cost of the DWI is € 65 000.

10 NO_x EMISSION ABATEMENT ACHIEVED WITH WATER INJECTION

The case study ship is equipped with common rail fuel injection system. The common rail system produces lower NO_x emissions by default compared with conventional fuel injection. The absolute NO_x emission level measured in the case study ship can be considered as a result of the combination of common rail and DWI. However, the DWI effect is separated for the purpose of this calculation.

The NO_x emission levels measured in the case study vessel may be affected by an equipment failure, as discussed in paragraph 8.3. However, the abatement level reached is within the levels reported in relevant literature. Comparison with other measurements conducted by Kymenlaakso University of Applied Sciences indicates that the NO_x abatement level in the case study ship is in the normal range.

10.1 Measurements aboard the case study vessel

The measurements were conducted during the normal route of the measured ship. The studied vessel was a cargo ship equipped with two main Wärtsilä 6L46F engines, which are 4-stroke, medium-speed diesel engines, each with a power output of 7,500 kW. For fuel injection, they are equipped with a common rail injection system. Both main engines are equipped with DWI. The DWI system was a new installation.

A typical sea run situation saw the engines under 80 per cent load. Harbour stops for loading and unloading normally took a couple of days. The main engines' running hours were around 24 000 each.

10.2 Measurement results and review

The measured NO_x levels are presented in Table 9. The measurement was taken using various settings for the DWI system. The emission level with the setting for full operation of the DWI system was chosen to represent the emission level. An excerpt from the measurement report is presented in Appendix 2.

Table 9. NO_x reduction levels with DWI.

NO_x without DWI	9.3 g/kWh
NO_x with DWI	6.3 g/kWh
NO_x reduction amount	3 g/kWh
Uncertainty ± 10 %	2.7 – 3.3 g/kWh
Reduction percentage	32 %

10.3 Amount of NOx reduction

Table 10. presents the calculation of the annual amount of abated NO_x emissions. The energy consumption calculations are presented in Appendix 5.

Table 10. Mass of NO_x reduced with DWI.

Annual main engine energy usage	51 300 MWh
Reduction amount	2.5 g/kWh
Abatement in one year	128 tons
Uncertainty ± 10 %	115 – 141 tons

11 COST CALCULATION OF NO_X ABATEMENT ACHIEVED WITH DWI

Table 11. presents the calculations of the price per abated ton of NO_x. The average annual cost is calculated for two main engines.

Table 11. Cost calculation per avoided ton with DWI.

Average annual cost of DWI	€ 65 000
NO_x emissions abated	128 tons
Price per abated ton	€ 508
Uncertainty ± 15 %	€ 430 – € 580

12 SUMMARY OF THE DWI SYSTEM STUDY

The measured vessel was equipped with two Wärtsilä 6L46F engines with common rail fuel injection. The typical engine load at sea is 80 per cent. The vessel operates continuously year-round with different ambient conditions.

The measured vessel has a direct water injection system installed as new. The DWI system reduces NOx emissions by approximately 130 tons per year. The cost of operating the DWI system is around € 500 per ton of abated emissions, which can be considered rather high. This may be the result of combining common rail and DWI technologies, which both have a positive effect on NOx emission reduction.

13 HUMID AIR MOTOR (HAM)

The Humid Air Motor is another wet method for decreasing NOx formation during the combustion process. In contrast to DWI, water is injected along with the combustion air. This is realised by saturating the combustion air before it enters the combustion chamber. The following sections explain the HAM technology in detail, from a definition and product names via the structure and process through to the reduction potential, advantages and disadvantages.

The number of HAM installations is limited, as is the amount of public information available.. This case study investigates the HAM installation on board Viking Mariella, which has acted as a public reference used by MAN.

13.1 Terms and definitions

The technology was invented by Swedish company Munters Euroform GmbH. In technical literature it can also be found under the term ‘charge, inlet or intake air humidification’. Furthermore, other companies carry the technology under their own specific brand names. For Finnish company Wärtsilä, it is known as WetPac and Steam Injected Diesel Engines (STID) and, from co-operation with Marioff Oy, it is known as a Combustion Air Saturation System (CASS). German company MAN in turn uses the common term, HAM, for systems that are suitable for 4-stroke engines and Scavenge Air Moistening (SAM) for systems that work on 2-stroke engines.

13.2 The structure of the HAM system

The main principle is to humidify the charge air of the engine to avoid high peak temperatures. 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 drawing in Figure 3.

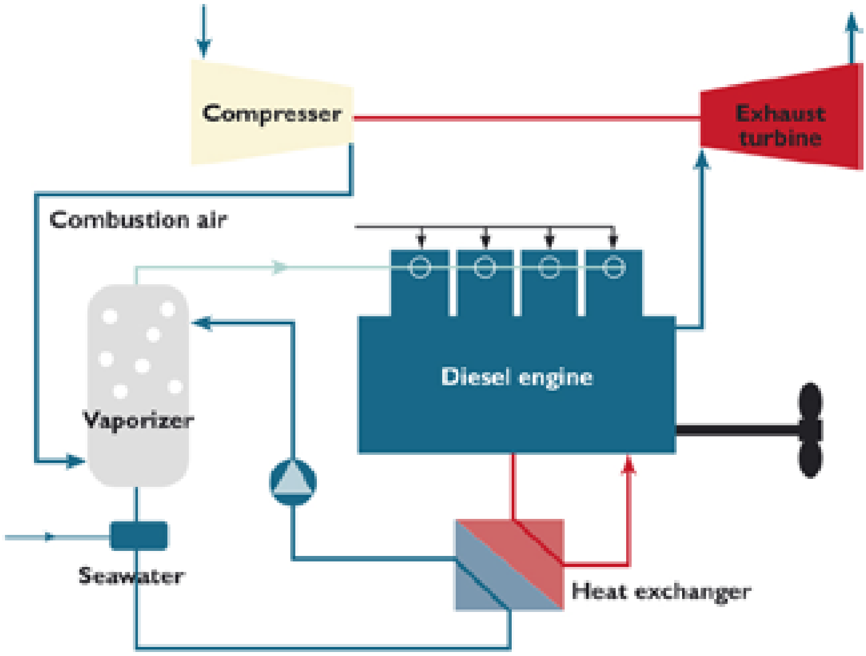

Figure 3. The basic working principle of the HAM system by MAN.

The turbocharger of the HAM system works like an ordinary turbocharger. 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 rotation generated by the turbine, the compressor can compress fresh air for the engine. The known advantages of a turbocharger, such as the availability of more oxygen for combustion, also apply to the HAM system.

The core component in the system is the humidifier, also known as a HAM unit. To mitigate harmful environmental effects, the material used to construct the humidifier must meet some requirements. Therefore, materials such as acid-proof steel and reinforced plastics are used to prevent corrosion. The HAM system turns off around 15 minutes before the main engines are stopped to dry the system and prevent corrosion in the engine.

The humidifier is constructed as a cylindrical vessel with three stages of surface-enlarging elements. The dimensions are based on the engine size. On board the study ship, it has a diameter of 1.3 metres and a length of 4 metres. When designing the length, it is important to bear in mind the evaporation time. For the width, a key factor is avoiding high flow velocities. Low 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 humidifier on 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. The bleed-off system consists of valves for draining water back into the sea and conductivity sensors to detect the salt content of the water. The amount of drained water varies between 1 and 25 per cent of all of the circulating water.

13.3 Process in the HAM system

Firstly, water is pumped into the catch tank. This can be seawater or grey water. Grey water is minor contaminated wastewater from sources such as showers and laundry systems.

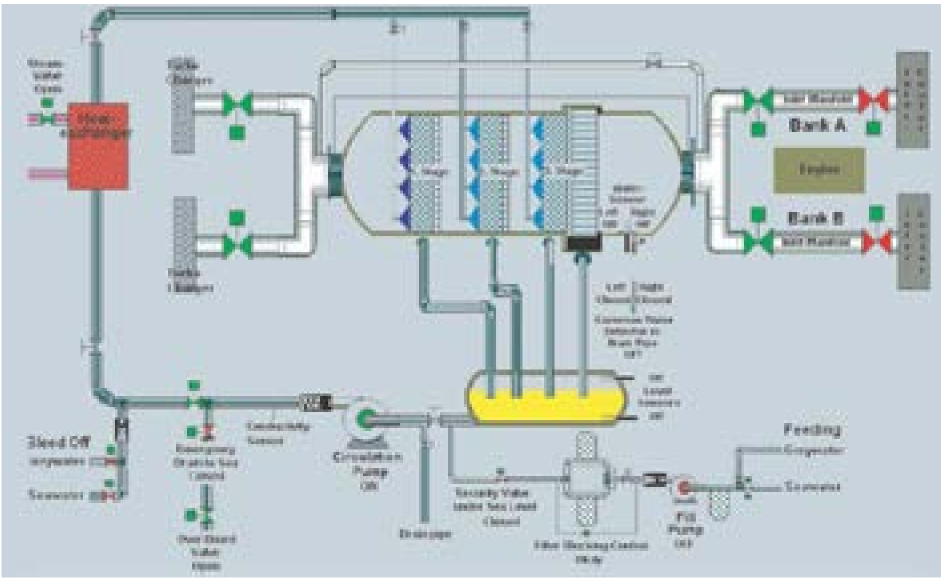

Figure 4. The flow chart diagram of a HAM system.

The drain water produced by the humidifier as an excess residue is also collected in the catch tank. The case study ship requires about 60 tons of water for a journey of approximately 250 nautical miles (463 km). Before the seawater reaches the catch tank it has to pass filters that separate algae and other raw contaminants. An additive can also be fed into the water to prevent the build-up of lime scale and other deposits.

After passing through a heat exchanger, marked in Figure 4. in red, the water is then pumped into the humidifier. This heat exchanger uses the heat of the exhaust gases or the engines' cooling water. The reason for using a heat exchanger is to preheat the seawater to achieve a higher NO_x reduction level. Without preheating, NO_x emissions of 4.5 g/kWh can be expected, but this can be reduced to below 3.5 g/kWh with heated water, according to information from MAN. Therefore, the water is preheated to a temperature of about 80 °C.

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 m/s can be assumed. Small water particles, 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 g per kg of dry air in the case of CASS. Grams or kilograms of water per kilogram of dry air is the standard unit of measurement of water contained. This figure is indicated in the literature with the letter X and can be found under the term 'water load'. The state of maximum saturated air is reached if the air contains its maximum amount of water at the specific temperature and pressure. It corresponds to a relative humidity of 100 per cent. If the saturation exceeds 100 per cent, the excess water will condense into water droplets.

The relative humidity of the charge air leaving the humidifier is about 98 per cent. As a general rule, air can contain more moisture the higher the air temperature is. Therefore, air that is heated through compression is quite applicable. This reaction is represented in Figure 5., which shows that the addition of heat is more beneficial than using the air in an adiabatic state. It can be also seen that a charge air temperature of about 70 °C is required to attain this highly saturated state. Normally the charge air is at a temperature between 40 and 50 °C. Possible sources of heat for preheating the charge air are engine coolant and exhaust gases, which can be led into the charge air.

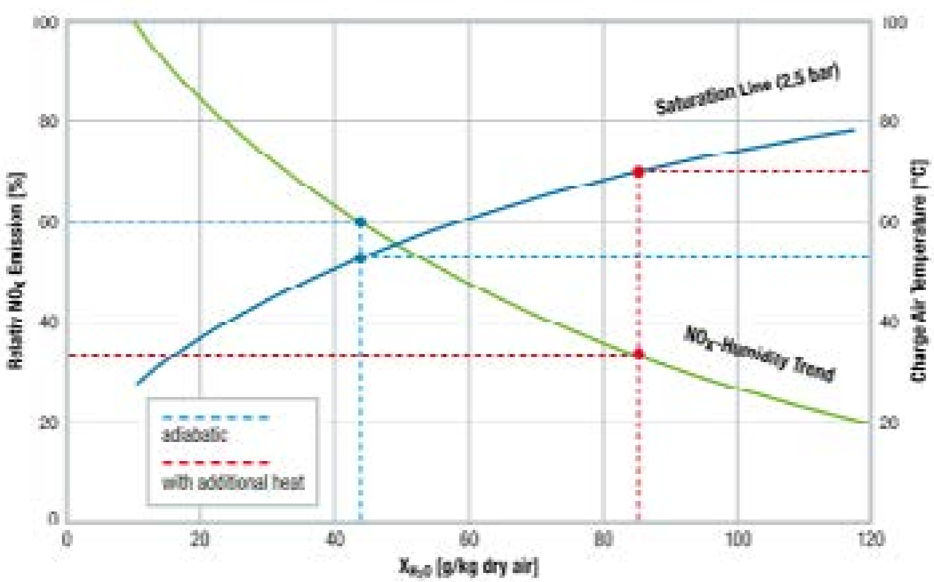

Figure 5. NO_x emissions with and without additional heating of the charge air.

During humidification, two main reactions can be determined. There is an increase in the specific heat capacity of the air-and-water mixture. This enables the charge air to contain more heat. At the same time, water replaces the oxygen in the air, leading to lower peak temperatures in the combustion chamber.

The amount of water that can feasibly be injected depends mainly on the pressure and temperature of the charge air. This means that a higher air temperature has a favourable effect on humidification, while higher pressure has the opposite effect. As the pressure increases, the intake air can contain smaller amounts of water, hindering the process.

Cooling the hot compressed charge air using water has the added benefit of almost obviating the need for a charge air cooler (CAC). Without a humidification system, the CAC would regulate (i.e., decrease) the temperature of the compressed charge air. The humidification system therefore replaces the CAC. In the interest of safety a CAC can be installed on a bypass loop in case the HAM system fails.

It is essential to cool the charge air because higher temperatures cause the density of the air to decrease. Consequently the air will contain less oxygen and the engine will have lower power and a greater thermal load. However, the water will evaporate in the humidifier with the help of surface-enlarging elements.

The humidifier on board M/S Mariella is made up of three surface-enlarging elements, so it has three injection stages in which preheated water is sprayed into the air flow. Seawater is distilled using an evaporation process. This prevents harmful substances such as salt or other pollutants in the seawater from passing into the cylinders of the engine.

Another device that protects the engine is the high-performance mist catcher, as named by MAN. This is situated at the end of the humidifier and, as its name suggests, it separates the water droplets from the saturated charge air. As 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 generalisation was confirmed by the field experience on-board, where a water-to-fuel ratio of 2.5 was determined. This represents the amount of water that is effectively injected into the cylinders. It does not equate to the total amount of water used. To guarantee a continuously low salt and mineral content in the circuit, a 'bleed-off' system is used. Furthermore, a safety drain into the sea is available, so the water can be bled off at any time. According to Lövblad and Fridell, 95 per cent of the water is reused in the cycle and 5 per cent is bled off.

An important adjustment that must be considered when installing a HAM system is the adaption of the turbocharger. Using a humidification system causes the temperature of the exhaust gases to decrease. This in contrast leads to an increase in density, enabling 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, it is necessary to raise the speed.

13.4 Reduction potential

Manufacturers make differing estimates of the amount of NO_x emissions that can be saved. Normally a reduction rate of 70 – 80 per cent is assumed. According to Wärtsilä, an abatement of 50 per cent, to approximately 7 g/kWh, is achievable with its humidification system, 'WetPac'. MAN indicates a reduction rate of 65 per cent if the charge air is preheated and 40 per cent if it is not.

On the Norwegian fishing vessel Kvannoy, which also uses the HAM system, NO_x emissions have been reduced by 61.3 per cent. The vessel's NO_x emissions were 9.3 g/kWh before the installation and 3.6 g/kWh after it. MAN invented the SAM system for two-stroke engines. According to MAN's own information, it can reduce NO_x emissions by 30 – 40 per cent.

13.5 Pros and cons

The previous chapter showed that the HAM system is a convenient and efficient method for reducing NO_x emissions. This is a summary of the advantages and disadvantages of this technology:

The HAM system distinguishes itself positively by the fact that it can be operated with simple seawater. Consequently, the operating costs are far smaller compared with other NO_x reduction methods that need fresh or distilled water, water with specific additives, or substances like urea. Furthermore, the HAM system is relatively light and compact, being 15 to 30 tons lighter than SCR. No storage tanks are required for fresh water, nor are additives needed. The only requirement is the physical proximity of the system to the engine, to avoid heat loss and to prevent the saturated air from condensing.

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 part of the engine. A further benefit is the greatly reduced consumption of lubricating oil. This is caused by much cleaner piston crowns. In general, the engine cleaner is and it is not necessary to clean the turbocharger. Also, TBO increases to 12 to 15 per cent, which reduces maintenance costs. Another advantage of the system is the reduced thermal load, which can extend the lifetime of engine components.

Furthermore, no significant increase in fuel oil consumption could be discerned, either on M/S Kvannoy or on M/S Mariella. In fact, M/S Mariella reported a decrease in fuel consumption of about five per cent. Also, there are no requirements for low-sulphur fuels.

14 OVERVIEW OF COSTS OF USING CHARGE AIR HUMIDIFICATION

The following information is gathered from several literary sources. The case study ship is a well-known reference for HAM systems, and most the cost information presented here is publicly available.

The HAM system in the case study does not require chemical agents or bunkered consumables.

14.1 Purchase and installation

The assumed capital costs include the costs of equipment and installation. The equipment includes a humidifier, a catch tank and a heat exchanger for preheating the water. Further components include pumps, filters, pipes and valves, as well as a control and monitoring system.

For newly built ships, a purchase cost of € 2 530 000 can be assumed. If the capital expenditure is stated per kilowatt, the average would be € 110 per kW, according to C. Hugi. If the system is retrofitted, capital expenditure will increase. Fortunately, it is possible to install the system while the engines are in daily operation, but such an installation necessitates in-depth planning. This is mirrored in the higher capital costs compared to the costs of a system on a newly built ship.

The capital costs for a retrofitted system are € 2 760 000, which results in an average of € 120 per kW. The cost of the retrofitted system on the case study ship was € 500 000 for each engine. Consequently, the total cost was € 2 000 000 to install the system on all four main engines. For each installed kilowatt of engine power, the capital costs were about € 87. The first installation was carried out while the ship was in daily use and the three following installations were carried out during its usual dry dock time.

14.2 Charge air humidification system lifespan and renewal

The advantage of the HAM system is that the most expensive components, such as the humidifier, the heat exchanger, the catch tank and the circulation pump, must only be installed once. It is not necessary to install these devices for each engine. To enable comparison, the lifespan of the three options is assumed to be 15 years.

14.3 Summary of the equipment costs

The equipment cost is annualised in Table 12. These costs are for a system installed in one session.

Table 12. The equipment cost of HAM system.

Purchase price	€ 2 000 000
Annualised, 15 years' lifespan	€ 133 000 per annum

14.4 Operating and maintenance costs

Operating and maintenance costs were calculated. According to the values from the case study ship, an expenditure of € 4000 per engine was assumed. As a result, it was calculated that the annual cost would be € 16 000 per ship. This is due to the ability of the HAM system to use seawater and grey water, which would otherwise be drained off. This figure is presented in Table 13.

Table 13. Operating and maintenance cost of HAM system.

Operating and maintenance	€ 16 000 per annum

14.5 Water considerations

The HAM system can use seawater or grey water, so water does not create a noteworthy cost. The marginal cost of water is included in the operating and maintenance cost.

14.6 Total cost and conclusion

Table 14. summarises the costs of HAM.

Table 14. Total cost of operating HAM.

	Annual cost
System design, purchase and installation expenses	€ 133 000
Operating costs	€ 16 000
Total	€ 149 000
Total with ± 10 % uncertainty	€ 135 000 – € 164 000

The cost structure is clearly weighted by system purchase costs. This case study relies on publicly available reference material for the life span of the system. The case study system will reach the end of its expected life span within the next two years. The continuation of the system – whether rebuilt or renovated – will provide new information in the future.

15 NO_X EMISSION ABATEMENT LEVEL ACHIEVED WITH CHARGE AIR HUMIDIFICATION

The NO_x emission level of the case study ship was measured with the HAM system operating normally. The NO_x emission level for the same engine type without the HAM system was calculated from three different engines with total of five measurements taken separately. The calculation for the reference level of NO_x is presented in Appendix 6.

15.1 Measurements aboard the case study vessel

The measurements were taken during the ship's normal activity. The studied ship was a ROPAX ship operating as cruise ship with daily harbour stops and waiting time for passengers. The ship has four main engines of type Pielstick 12PC2.6 with a nominal power of 5750 kW.

A typical sea run situation saw the engines operating at 75 – 80 per cent load. The main engines run for between 113 000 and 133 000 hours.

15.2 Measurement results and review

The measured NO_x levels are presented in Table 15. Measurements were taken for each of the four engines. The NO_x emission presented here is an average of the four measurements. The averaging details are presented in Appendix 3.

Table 15. NO_x reduction levels with HAM.

<table>
<tr><td></td><td>Average</td><td rowspan="6">The figures adjacent are calculated by averaging several measurement results. The calculation is presented in Appendix 3.</td></tr>
<tr><td>NO_x without HAM</td><td>16.7 g/kWh</td></tr>
<tr><td>NO_x after HAM</td><td>5.9 g/kWh</td></tr>
<tr><td>NO_x reduction amount</td><td>10.8 g/kWh</td></tr>
<tr><td>Uncertainty ±10 %</td><td>9.7 – 11.8 g/kWh</td></tr>
<tr><td>Reduction percentage</td><td>65 %</td></tr>
</table>

15.3 Amount of NO_x reduction

The total mass of abated NO_x is calculated in Table 16. The total annual energy consumption is calculated in Appendix 5.

Table 16. Mass of NO_x reduced with HAM.

Annual main engine energy usage	46 000 MWh
Reduction amount	10.6 g/kWh
Abatement in one year	528 tons
Uncertainty ± 10 %	476 – 581 tons

16 COST CALCULATION OF NO_X ABATEMENT ACHIEVED WITH CHARGE AIR HUMIDIFICATION

Table 17. presents the calculations of the price per abated ton of NO_x.

Table 17. Price calculation per abated ton with HAM.

Average annual cost of running HAM	€ 149 000
Abated NO_x emissions	528 tons
Price per abated ton	€ 280
Uncertainty ± 15 %	€ 240 – € 325

17 SUMMARY OF THE HAM SYSTEM STUDY

The measured vessel was equipped with four Pielstick 12PC2.6 main engines with a nominal power of 5750 kW. The ship operates as a cruise vessel with daily port stops of several hours. The vessel operates continuously all year under different ambient conditions. The typical engine load at sea is 75 – 80 per cent.

The measured vessel has had a HAM charge air humidification system retrofitted. The system reduces NO_x emissions by approximately 530 tons per year.

The cost of the NO_x abatement achieved is around € 280 per ton.

18 COMPARISON OF THE ABSOLUTE NO_X EMISSION LEVELS

The case study abatement systems can be compared with absolute NO_x emission levels. This comparison is useful for reference purposes. However, a full analysis is beyond the scope of this report. This information is presented below in Table 18. with no conclusions attached.

Table 18. NO_x emission comparison.

Abatement technology	Reported average NO_x emission of case study ships
Selective catalytic reaction (SCR)	2.7 g/kWh
Direct water injection (DWI)	6.3 g/kWh
Humid air motor (HAM)	5.9 g/kWh
Target NO_x level according to Marpol Annex VI.	2.2 – 2.4 g/kWh

19 COMPARISON OF THE COST CALCULATION OF THE STUDIED TECHNOLOGIES

The case study ships and abatement technologies differ in many ways. The price components are different depending on whether the system includes consumable chemicals or wearing parts. The main cost component of SCR technology is the price of the chemical reagent (urea) used in the process. The price of urea is subject to change and therefore the cost of the system can vary over time. The water-based technologies are also different in terms of their cost compositions. The DWI technology needs a periodic part refit when injector parts wear out. HAM technology has no such special parts or consumables liable to expensive replacement; instead, the drawback of HAM is the highest initial cost.

The case study results of price per abated ton of NO_x are presented in Table 19. The comparison figures from a literature review are presented in Table 20.

Table 19. Summary of the case study results

Abatement technology	Cost per ton of NO_x abated
Selective catalytic reaction (SCR)	€ 800
Direct water injection (DWI)	€ 510
Humid air motor (HAM)	€ 280

Table 20. Literature references. The cost per ton of NO_x abated, calculated as averages from the source information.

	ENTEC	Sjöfartsverket
Selective catalytic reaction (SCR)	€ 400	€ 630
Direct water injection (DWI)	€ 345	€ 380
Humid air motor (HAM)	€ 250	€ 250

The one distinguishable detail of Table 19. is the figure related to the DWI technology. It seems high compared to the literature references listed in Table 20. This can be explained by the engine used on the measured ship. The measured ship has a relatively new engine with common rail technology. The common rail technology improves the properties of the fuel injection process and results in lower NO_x emissions by default.

The previous measurements taken by Kymenlaakso University of Applied Sciences confirm the benefit of the common rail system. The same engine type as in the DWI case study produces significantly higher NO_x emissions without common rail.

However, the comparison presented here is limited only to a cost analysis of the NO_x abatement equipment. The result is valid with the given remarks, and the benefit of combining DWI with common rail technology will be the subject of further studies.

20 SUMMARY AND CONCLUSIONS

This paper presented a report of three case studies of three different NO_x emission reduction technologies. The emission information was gathered from actual on-board measurements. The measurements were made during the normal operation of the ships.

The costs of emission abatement systems on the case study vessels were investigated. The emission reduction level was set against the cost of the system and a comparable NO_x reduction price was calculated for each system. The NO_x reduction prices of each of the case study subjects were compared.

The comparison reveals essential differences in the price of the abated NO_x emissions. The cost structure of the abatement technologies also proved to be different in each of the cases.

The purpose of this report is to provide first-hand information from the actual operation environments of the abatement systems described. The results reported here are not analysed further in this regard.

References and bibliography

This bibliography does not include references to personal correspondence. Confidential manufacturer records and documents are also withheld. References are in alphabetical order.

Andijani, I., Malik, A., Sulfur and vanadium induced hot corrosion of boiler tubes, D cember 2004, Page 1, http://www.swcc.gov.sa/files/assets/Research/Technical% 20Papers/Corrosion/SULFUR%20AND%20VANADIUM%20INDUCED%20HOT 20CORROSION%20OF%20BOILER%20TUBES....pdf [Accessed 17 May 2013]

Commodity Prices. http://www.indexmundi.com/commodities/ [Accessed 1 August 2012]

Coquillaud, P., Graf, K. The MAN B&W V40/50 Diesel engine, 2002, Page 11. http://vk.od.ua/15301.pdf [Accessed 18 May 2013]

Corbett, J.J., Koehler, H.W. 2003. Updated emissions from ocean shipping. Journal of geophysical research, vol. 108. American Geophysical Union.

Corbett, J.J, Wang, C., Winebrake, J.J., Green, E. 2007. Allocating and forecasting of global ship emissions. Clean air task force. http://www.ceoe.udel.edu/cms/jcorbett/FOEI_final-IMO_submission_Annex.pdf [Accessed 2 August 2012]

Davis, M.L., Cornwall, D.A. 2008. Introduction to environmental engineering 4th edition. McGraw-Hill. New York.

ENTEC. 2005. Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments (final report), task 2. European Commission Directorate General Environment. http://ec.europa.eu/environment/air/pdf/task2_general.pdf [Accessed 1 August 2012]

Exhaust Gas After-Treatment by SCR Catalysts. H+H Umwelt- und Industrietechnik GmbH. www.HuHGmbH.com http://www.nho.no/getfile.php/filer%20og%20vedlegg/SCR%20-%20H%2BH.pdf [Accessed 10 July 2013]

Geller, W. Thermodynamik für Maschinenbauer, 3rd edition, 2005, Page 211

Genesis Engineering Inc., Levelton Engineering Ltd. October 2003. Non-road diesel emission reduction study, Page 40, 105, www.ecy.wa.gov/programs/air/pdfs/non-roaddieselstudy.pdf [Accessed 23 April 2013]

Hefazi Hamid, Rahai Hamid R. 2008. EMISSION CONTROL TECHNOLOGIES FOR OCEAN GOING VESSELS (OGVs). California State University, Long Beach. http://www.arb.ca.gov/research/apr/past/06-327.pdf [Accessed 10 July 2013]

Hugi, C., Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments, Task 2b – NOx Abatement, August 2005, Page 6, 45 http://ec.europa.eu/environment/air/pdf/task2_nox.pdf [Accessed 20 April 2013]

Insko. 1992. Insko julkaisu 85-92. Savukaasupäästöjen vähentäminen 1 – 5, osa 5: Kaasupäästöjen vähentämisen tekniikat. Insinöörien koulutuskeskus Oy, Helsinki.

International maritime organization. 2011. Marpol Consolidated edition 2011. IMO, London.

International Maritime organization. 2006. Pollution prevention equipment under Marpol, 2006 edition. IMO, London.

De Jonge Emily, Hugi Christoph, Cooper David. 2005. Commission Directorate General Environment Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments. Entec UK Limited, England. http://ec.europa.eu/environment/air/pdf/task2_nox.pdf [Accessed 10 July 2013]

Kageson, P., Bahlke, C., Hader, A., Hübscher, A., Market Based Instruments for Abatement of Emissions from Shipping, March 2008, Page 41, 45ff http://www.gauss.org/img/pool/Forschung.MBI%20Baltic%2005_03_2008_3.pdf [Accessed 28 April 2013]

Kalli Juha, Repka Sari. 2010. "Baltic NECA – economic impacts" – Preliminary study report by the University of Turku, Centre for Maritime Studies. http://meeting.helcom.fi/c/document_library/get_file?p_l_id=18819&folderId=1107843&name=DLFE-41643.pdf [Accessed 10 July 2013]

Krishnan, R. 2001. SCR economics for diesel engine. Diesel & Gas turbine worldwide, July-August 2001. http://www.rjm.com/pdf/screcon.pdf [Accessed 1 August 2012]

Lindstedt, U., Andersson, P., Löfblad, G., Löfblad, E. Bara naturligt försurning. Bilaga 5: Konsekvensanalys av förslag till nytt delmål för utsläpp av svavel och kväve från sjöfart. Naturvårdsverket. http://www.naturvardsverket.se/Documents/publikationer/620-5780-0.pdf [Accessed 8 August 2012]

Lövblad G., Fridell E. Experiences from use of some techniques to reduce emissions from ships, May 2006, Page 18f, http://www.profu.se/pdf/experiences.pdf [Accessed 17 April 2013]

Lövblad Gun, Fridell Erik. 2006. Experiences from use of some techniques to reduce emissions from ships. Göteborg. http://www.profu.se/pdf/experiences.pdf [Accessed 10 July 2013]

Man Diesel Selective catalytic reduction. http://cleantech.cnss.no/wp-content/uploads/2011/06/year-unknown-MAN-BW-SCR.pdf [Accessed 1 August 2012]

MAN Diesel SE, NOx-Reduction by Charge Air Humidification, 14. May 2008, Page 5, 13, http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd= 1&ved=0CDMQFjAA&url=http%3A%2F%2Fwww.nho.no%2Fgetfile.php%2FMicr soft%2520PowerPoint%2520-%2520HAM_Oslo_2008 0514.pdf&ei=lVp2Uc3REMuw4QTLnoC4Ag&usg=AFQjCNERaU4iK0Oj9WI2UbXGdPtm98Rg&bvm=bv.45512109,d.bGE [Accessed 18 May 2013]

MAN Diesel & Turbo SE, 61.3 percent NOx Reduction after Retrofit of HAM System, September 2010, http://www.man.eu/en/press-and-media/press-releases/61.3-percent-NOx-Reduction-after-Retrofit-of-HAM-System--57217.html [Accessed 20 April 2013]

Marine Propulsion December/January 2011/12. SCR Retrofits for Finnish icebreaker pair.

Mørebunkers AS. Product specification, Urea. http://morebunkers.no/images/files/MB_UREA_Product_Specification.pdf [Accessed 14 August 2012]

Nesse, H. 2008. Wärtsilä low NOx solutions. http://www.nho.no/getfile.php/W%E4rtsil%E4%281%29.pdf [Accessed 16 July 2012]

Niskanen, V. 1985. Kaasumittaukset. Insinööritieto Oy.

NO_x Emissions from Merchant Ships. http://www.marinelink.com/news/article/nox-emissions-from-merchant-ships/305152.aspx [Accessed 1 August 2012]

Prior, A., Jääskelainen, H., Walsh, J., NO_X emission study: An Investigation of Water-Based Emission Control Technologies, October 2005, Page 34, 69, http://s3.amazonaws.com/zanran_storage/www.tc.gc.ca/ContentPages/72655314.pdf [Accessed 20 April 2013]

Project CNSS, Direct Water Injection (DWI), http://cleantech.cnss.no/air-pollutant-tech/nox/direct-water-injection-dwi/ [Accessed 5 May 2013]

Räsänen, P. 2000. Laivatekniikka. Turun ammattikorkeakoulu, Turku.

Sjöfartens bok. 2011.. Svensk sjöfarts tidning förlag AB, Göteborg.

Steinhilber T., Einfluss der Wasser- oder Emulsionseinspritzung auf die homogene Dieselverbrennung, December 2007, Page 110f, 113, 132, 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 [Accessed 25 April 2013]

The institute of Marine Engineers. 1999. Marpower 99 Conference proceedings: Advanced marine machinery systems with low pollution and high efficiency. London.

Torvela, H. 1994. Measurement of atmospheric emissions. Springer-Verlag, London.

Vapalahti, H. 2011. Suomen kuvitettu laivaluettelo 2011. Judicor Oy, Kotka.

Vestheim-Vigeland, H. 2012. SOx and Scrubbers. Requirements and DNV involvement from a Class perspective. Åland Maritime Day 2012. Det Norske Veritas AS.http://www.sjofart.ax/files/hakan_vestheim_vigeland_class_approval_and_approved_scrubber_systems.pdf [Accessed 16 July 2012].

Wahlström, J., Karvosenoja, N., Porvari, P., Ship emissions and technical emission reduction potential in the Nothern Baltic Sea, 2006, Page 9, 36f, http://www.environment.fi/download.asp?contentid=55273&lan=en [Accessed 22 April 2013]

Wahlström, J., Karvosenoja, N., Porvari, P. 2006. Ship emissions and technical emission reduction potential in the Northern Baltic Sea. Finnish Environment Institute. http://www.environment.fi/download.asp?contentid=55273&lan=en [Accessed 16 July 2012]

Woodyard, D. Pounder's Marine diesel engines 7th edition. 1998. Butterworth-Heinemann, Oxford.

Woodyard, D. Pounder's marine diesel engines and gas turbines, 9th edition, 2009, Page 8, 9, 73f, 173, 235f, 508.

Wright, A.A. 2000. Exhaust emissions from combustion machinery; MEP Series, volume 2, part 20. The Institute of marine engineers, London.

Wärtsilä, Technology Review, October 2010, Page 6, 8, http://www.dieselduck.net/machine/01%20prime%20movers/rhapsody%20de1/Wartsila%20W46.pdf [Accessed 26 April 2013]

APPENDIX 1. Summary of SCR measurement report

Table A1–1. Average results of NO_x measurements before and after catalytic converter, main engine 1.

Subject	Load (%)	NO_x dry (ppm)	NO_x (mg/(n)m^3)		NO_x (g/kWh)	
ME1 after SCR	75	229	460	± 7 %	2.15	± 10 %
ME1 before SCR	75	1104	2216	± 7 %	10.38	± 10 %

Table A1–2. Average results of NO_x measurements before and after catalytic converter, main engine 2.

Subject	Load (%)	NO_x dry (ppm)	NO_x (mg/(n)m^3)		NO_x (g/kWh)	
ME2 after SCR	75	317	637	± 7 %	3.16	± 10 %
ME2 before SCR	75	1034	2079	± 7 %	10.29	± 10 %

Table A1–3. Average results of O_2 measurement

Subject	Load (%)	O_2 dry (%)	O_2 dry uncertainty
ME1	75	12.1	11.9 – 12.3
ME2	75	12.6	12.4 – 12.8

Table A1–4. Average results of CO measurement

Subject	Load (%)	CO dry (ppm)	CO (mg/(n)m^3)		CO (g/kWh)	
ME1	75	167	204	± 7 %	1.13	± 10 %
ME2	75	164	201	± 7 %	1.17	± 10 %

Table A1–5. Average results of exhaust gas temperature and exhaust gas flow rate

Subject	Load (%)	Temp (°C)	Temp uncertainty (°C)	Flow rate (m^3(n)/s)
ME1	75	300	± 2	7.1
ME2	75	305	± 2	7.4

APPENDIX 2. Summary of DWI measurement report

Table A2-1. Average results of NO_x measurements with and without water injection, main engine 2.

Subject	Load (%)	NO_x dry (ppm)	NO_x (mg/(n)m^3)		NO_x (g/kWh)	
ME2 after DWI	81	640	1291	± 7 %	6.31	± 10 %
ME2 before DWI	81	940	1897	± 7 %	9.27	± 10 %

Table A2–2. Average results of NO_x measurements without water injection, main engine 1.

Subject	Load (%)	NO_x dry (ppm)	NO_x (mg/(n)m^3)		NO_x (g/kWh)	
ME1 no DWI	77	890	1796	± 7 %	8.78	± 10 %

Table A2–3. Average results of O_2 measurement

Subject	Load (%)	O_2 dry (%)	O_2 dry (%) uncertainty
ME1 no DWI	77	13.8	13.6 – 14.0
ME2 before DWI	81	13.8	13.6 – 14.0
ME2 after DWI	81	13.8	13.6 – 14.0

Table A2–4. Average results of CO measurement

Subject	Load (%)	CO dry (ppm)	CO (mg/(n)m^3)		CO (g/kWh)	
ME1 no DWI	77	52	64	± 7 %	0.33	± 10 %
ME2 before DWI	81	60	51	± 7 %	0.39	± 10 %
ME2 after DWI	81	60	51	± 7 %	0.39	± 10 %

APPENDIX 3. Summary of HAM measurement report

Table A3–1. Average results of NO_x measurements after HAM, main engines 1, 2, 3, 4.

Subject	Load (%)	NO_x dry (ppm)	NO_x (mg/(n)m^3)		NO_x (g/kWh)	
ME1	80	483	980	± 7 %	5.93	± 10 %
ME2	73	380	767	± 7 %	3.76	± 10 %
ME3	70	901	1822	± 7 %	9.55	± 10 %
ME4	80	417	844	± 7 %	4.36	± 10 %

Table A3–2. Average results of O_2 measurement

Subject	Load (%)	O_2 dry (%)	O_2 dry (%) uncertainty
ME1	80	15.2	15.0 – 15.4
ME2	73	13.6	13.4 – 13.8
ME3	70	14.1	13.9 – 14.3
ME4	80	14.0	13.8 – 14.2

Table A3–3. Average results of CO measurement

Subject	Load (%)	CO dry (ppm)	CO (mg/(n)m^3)		CO (g/kWh)	
ME1	80	151	186	± 7 %	1.26	± 10 %
ME2	73	114	140	± 7 %	0.75	± 10 %
ME3	70	91	112	± 7 %	0.64	± 10 %
ME4	80	107	132	± 7 %	0.74	± 10 %

APPENDIX 4. Measurement arrangements in the case study vessels (1/2)

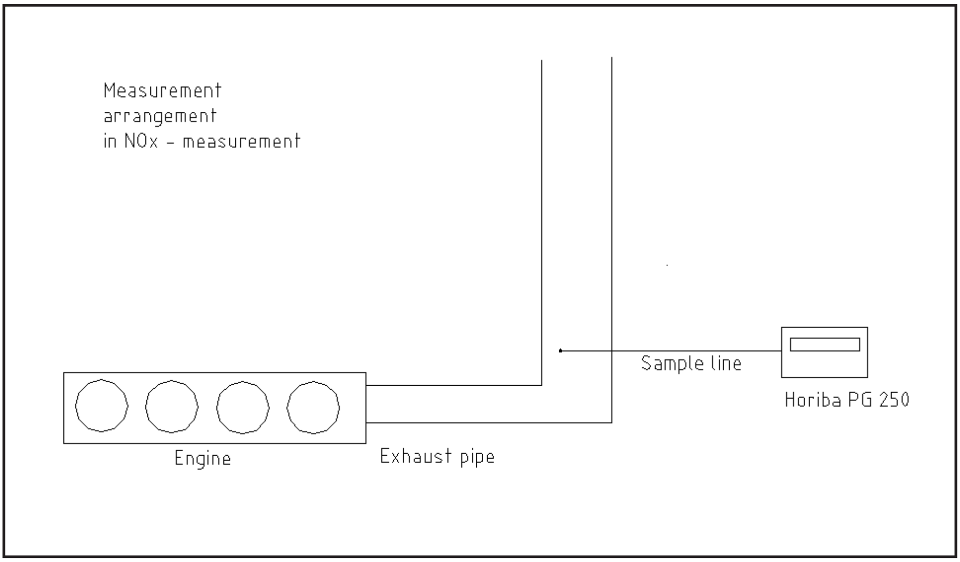

Figure A-4-1. Measurement setup for DWI and HAM measurement.

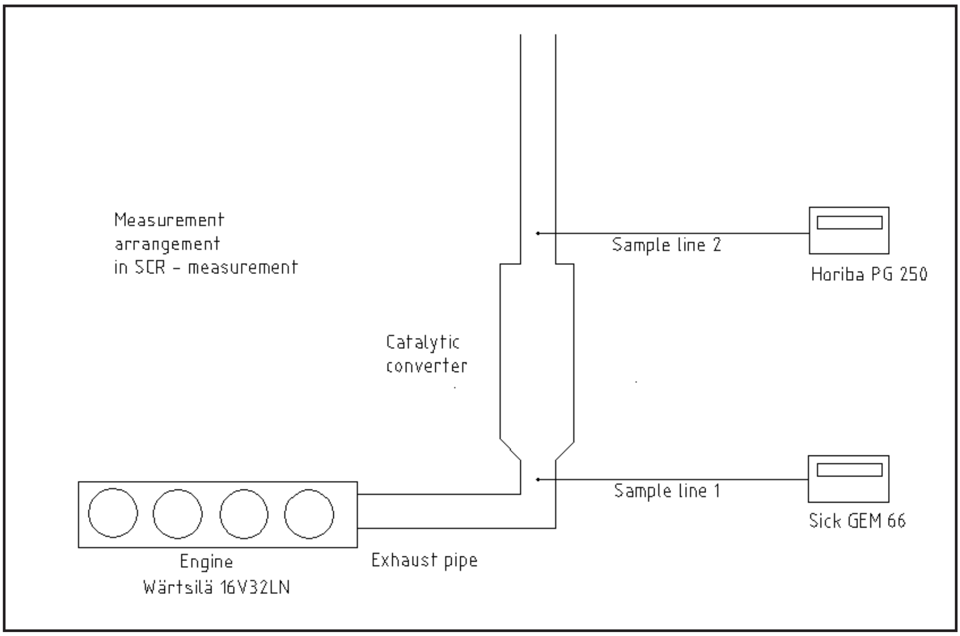

Figure A-4-2. Measurement setup for SCR measurement.

APPENDIX 4. Measurement arrangements in the case study vessels (2/2)

Measurement results were collected by the data logger every 30 seconds during the measurement period. The readings were also written down on measurement forms every 15 minutes. The measurement configuration is illustrated in Figure A–4–1.

The measurement arrangement for the SCR system required two simultaneous measurements. The exhaust gas was sampled in the exhaust gas pipe and after the SCR system. The positions of the measurement equipment are illustrated in Figure A–4–2. All the equipment and analysers are approved for emission determination according to the ISO 8178–2 standard and Annex VI to MARPOL 73/78 (IMO NO_x code) or standards equivalent to these.

Measurements were taken by engineer Mikko Nykänen and technician Marko Piispa from Kymenlaakso University of Applied Sciences. The measurement dates were 8 – 10 May 2012, 17 – 19 October 2012 and 7 – 9 March 2013. Equipment and methods are listed in Tables A4–1. and A4–2.

Table A4–1. Methods and principles.

Component	Principle	
NO_x	Chemiluminescence	Non-diluted
O_2	Paramagnetic detection	Non-diluted
SO_2	IR	Non-diluted

Table A4–2. Equipment list.

Component	Equipment	Range	Calibration gas
SO_2	HORIBA PG 250	0 – 3000 ppm	0 / 89 ppm
NO_x	HORIBA PG 250 Sick GME 66	0 – 2500 ppm 0 – 10000 ppm	0 / 200 ppm / 900 ppm
CO	HORIBA PG 250	0 – 5000 ppm	0 / 400 ppm
CO_2	HORIBA PG 250	0 – 20 %	0 / 10 %
O_2	HORIBA PG 250	0 – 25 %	0 / 20.9 %
Flow	MIKOR TT570SV		
Temperature	FLUKE thermo	0 – 1000 °C	

APPENDIX 5. Total energy consumption calculations (1/3)

Engine load calculation of the DWI case study vessel

The case study vessel had been operating for 1760 days since completion, up to the measurement date. The vessel has two main engines with running hours of 24 740 and 23 778. (Sources: Ship engine logs, GL online). The main engines are Wärtsilä 6L46F with a nominal power of 7500 kW.

The following calculation gives the annual run time of the engines:

$$\frac{24670\ h + 23778\ h}{\frac{1760\ d}{365\ \frac{d}{a}}} = 10062\ \frac{h}{a}$$

The calculation gives the total engine run time. At this point an assumption of the engine load distribution between sea running and manoeuvring is made. For the purposes of this calculation, 80 % of the ship's running hours are assumed to be with engines at 80 % load and the remainder at 10 % load. These load values represent the sea run and harbour manoeuvring situations.

$$0.8 * 80\% + 0.2 * 10\% = 68.0\ \%$$

This assumption is consistent with the vessel's logs. However, the logs were available only for a short period of time.

Combining the total run time and average load results gives a value for work performed:

$$68\% * 10062\ \frac{h}{a} = 6842 \frac{h}{a}$$

$$6842 \frac{h}{a} * 7500\ kW = 51.3\ GWh$$

The calculation gives a total annual energy consumption of 51.3 GWh. This figure represents the total amount of work performed during one year.

Engine load calculation of the HAM case study vessel

The case study vessel had been operating for 10 220 days since completion, up to the measurement date. The vessel has four main engines with running hours of 132 887, 115 236, 113 092 and 128 248. (Sources: Ship engine logs, DNV online). The main engines are Pielstick 12PC2.6 with a nominal power of 5750 kW.

The following calculation gives the annual run time of the engines:

$$\frac{132887\,h + 115236\,h + 113092\,h + 128248\,h}{\frac{10220\,d}{365\,\frac{d}{a}}} = 17481\,\frac{h}{a}$$

The calculation gives the total engine run time. At this point an assumption of the engine load distribution between sea running and manoeuvring is made. For the purposes of this calculation, half of the ship's running hours are assumed to be with engines at 80 % load and the other half at 10 % load. These load values represent the sea run and harbour manoeuvring situation.

$$0.5 * 80\% + 0.5 * 10\% = 45.5\ \%$$

This assumption is consistent with the vessel's logs. A typical sea run situation sees two or three main engines running at 75 % load.

Combining the total run time and average load gives a value for work performed:

$$45.5\% * 17471\,\frac{h}{a} = 7954\frac{h}{a}$$

$$7945\frac{h}{a} * 5750\,kW = 45.7\,GWh$$

The calculation gives a total annual energy consumption of 45.7 GWh. This figure represents the total amount of work performed during one year. The ship operates as a cruise vessel with daily port stops of several hours.

Engine load calculation of the SCR case study vessel

The vessel has four main engines of type Wärtsilä 16V32LN with a nominal power of 6560 kW.

The ship's logs were examined for an eight-day period. The ship's personnel were consulted and the ship's performance for eight days was found to be accurately representative of its normal operation.

The main engine operation time during the eight-day period was 439 hours. The total number of running hours for a one-year period is calculated as follows:

$$\frac{439\ hours}{8\ days} * 365\ days\ = 20\ 030\ \frac{h}{a}$$

The calculation gives the total engine run time. The engine load was monitored during the measurement and the ship's logs were examined. The average load was found to be 72.1 %. This figure is relatively high. However, the vessel runs continuously for 21 hours per day with only short harbour visits. The schedule is tight and it is typical that three or four engines are operating during sea runs. Harbour manoeuvring is sometimes carried out with one engine.

$$72.1\% * 20\ 030\ \frac{h}{a} = 14441\frac{h}{a}$$

$$14441\frac{h}{a} * 6560\ kW\ = 94.7\ GWh$$

The calculation gives a total annual energy consumption of 94.7 GWh. This figure represents the total amount of work performed during one year.

APPENDIX 6. HAM measurement calculations and averaging (1/2)

The following tables, numbered A6–1. and A6–2. Present the NO_x emission values of Pielstick 12PC2.6 2VE-400 engines without any abatement technology. Measurements were conducted by Kymenlaakso University of Applied Sciences' emission measurement laboratory. Results are calculated from a total of five measurements of three engines on board two ships.

Table A6–1. Reference engine in ship A. Measurement year: 2012.

Engine (nr)	Load (%)	NO_x dry (ppm)	NO_x (mg/(n)m^3)		NO_x (g/kWh)	
ME A3 (570)	78	1537	3096	± 7 %	16.49	± 10 %
ME A3 (570)	74	1560	3143	± 7 %	16.54	± 10 %
ME A3 (570)	73	1706	3434	± 7 %	17.49	± 10 %

Table A6–2. Reference engines in ship B. Measurement year: 2011.

Engine (nr)	Load (%)	NO_x dry (ppm)	NO_x (mg/(n)m^3)		NO_x (g/kWh)	
ME B1 (15313)	74	1237	2493	± 7 %	16.09	± 10 %
ME B3 (15619)	74	1302	2623	± 7 %	16.69	± 10 %

The average NO_x emissions calculated from these results are as follows:

$$\frac{16.09+16.69+16.49+16.54+17.49}{5} = 16.7\ [g / kWh] \pm 10\ \%$$

APPENDIX 6. HAM measurement calculations and averaging (2/2)

The table number A6–3. presents the NO_x emission values of Pielstick 12PC2.6 2VE-400 engines with HAM installed.

Table A6–3. Measurement results with HAM installed.

Engine (nr)	Load (%)	NO_x dry (ppm)	NO_x (mg/(n)m^3)		NO_x (g/kWh)	
ME1	80	483	980	± 7 %	5.93	± 10 %
ME2	73	380	767	± 7 %	3.76	± 10 %
ME3	70	901	1822	± 7 %	9.55	± 10 %
ME4	80	417	844	± 7 %	4.36	± 10 %

The ME3 result seems inconsistent with the results of the other engines. Also, the CO measurement and the temperature level from the measurement report suggest that the value may contain error. Therefore, the highest and lowest measurements were excluded from the calculation of the average, giving the following:

$$\frac{5.93+4.36}{2} = 5.15 \approx 5.2 \text{ [g / kWh]} \pm 10\ \%$$

Direct water injection

Wärtsilä has tested a system on a Silja Line passenger ship, M/S Silja Symphony, with a water-to-fuel ratio of approximately 40 %, resulting in a reduction in NO_x emissions of approximately 50 %. Wärtsilä has completed its engine testing for direct water injection using fuels with a sulphur content of less than 3 %.

Further research is required to assess this system's performance and additional maintenance costs if high-sulphur fuel is used. Table A7–1. shows the cost effectiveness of removing NO_x based on the results obtained from M/S Silja Symphony.

Table A7–1. Cost effectiveness of DWI.

Abatement type	Ship type	Emission	Small vessel	Medium-sized vessel	Large vessel
Direct water injection	New	NO_x	$ 371.31 per ton	$ 325.23 per ton	$ 311.68 per ton

A humidification, or humid air motor, system has been tested on one ship, the M/S Mariella, with positive results. However, as stated, the initial investment cost for installing such a system has prevented large-scale adoption on OGVs. Table A7–2. shows the cost effectiveness of NO_x removal for the test performed aboard M/S Mariella.

Table A7–2. Cost effectiveness of HAM.

Abatement type	Ship type	Emission	Small vessel	Medium-sized vessel	Large vessel
Humid air motors	New	NO_x	$ 242.12 per ton	$ 207.79 per ton	$ 178.88 per ton
Humid air motors	Retrofit	NO_x	$ 276.45 per ton	$ 254.77 per ton	$ 237.60 per ton

Direct Water Injection (DWI)

Installation:

- When installed on new ships, the cost is estimated at € 345 – € 411 per ton of NO_x abatement.

- The cost of retrofitting is relatively high, due to the expected need of new cylinder heads, which represent around a quarter of the cost of a new engine (around € 50 per kW)

Operation:

- High water quality is necessary, 90 g/kWh (45 % water injection rate). Entec calculated with a distilled water cost estimated at € 15 per m^3. In many cases, drinking water is used at a lower cost.

Life span:

- The life span of a DWI system is estimated at around 4 years. The rest of the equipment is estimated to have a life span of 25 years.

Humid Air Motor (HAM)

Installation:

- When installed on new ships, the cost is estimated at € 198 – € 268 per ton of NO_x abated. As a retrofit, the system costs € 263 – € 306 per ton of NO_x abated.

- Costs are € 90 – € 130 per kW for newly built engines and € 110 – € 130 per kW for retrofit.

Operation:

- The maintenance cost is € 4000 per year for a 5.7 MW engine, or approximately € 0.15 per MWh.

Life span:

- The life span if durable – non-corrosive or galvanised – material is used is 25 years.

Selective Catalytic Reduction (SCR)

Installation:

- For new ships using MD, the cost is estimated at € 313 – € 413 per ton of NO_x abated. For new ship using high-sulphur residual oil (> 1.5 % S), the estimated cost is € 526 – € 740 per ton of NO_x abated.

- Costs are € 40 – € 60 per kW for newly built engines and € 60 – € 100 per kW for retrofit.

Operation:

- Urea solution: € 170 per ton or € 2.6 per MWh. There are indications that a lower urea price of € 120 – € 140 per ton may be possible due to several competing companies delivering urea. Transporting urea may form a considerable part of the cost.

- The equipment must be maintained. Entec estimated cleaning requirements to cost € 8000 per ship per year. The need for maintenance depends on the fuel used. An estimate of the operating cost for one ship (excluding financing) is € 10 000 per year.

Life span:

- The catalyst is estimated to require a rebuild every 20 000 hours of operation when using residual oil.

Based on Entec 2005. Total costs of the DWI system.

Table A7–3. Costs of DWI.

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

Based on Entec 2005. Total costs of the HAM system.

Table A7–4. Costs of HAM.

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

Based on Entec 2005. The cost effectiveness of NO_x abatement systems.

Table A7–5.Cost effectiveness per ton of NO_x emission abated.

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

Table A7–6. Cost of NO_x abatement € per ton of NO_x abated. (Based on ENTEC 2005).

Vessel size/type	Small	Medium	Large
DWI new	411	360	345
HAM new	268	230	198
HAM retrofit	306	282	263

Table A7-7. SCR inside SO_2 ECA, € per ton NO_x abated.

Vessel size/type	Small	Medium	Large
SCR New	543	424	398
SCR Retrofit	613	473	443

APPENDIX 8. The emission levels of DWI systems with different numbers of nozzles operating

Figures A–8–1. and A–8–2. show measured NO_x levels presented as a function of the number of nozzles in operation.

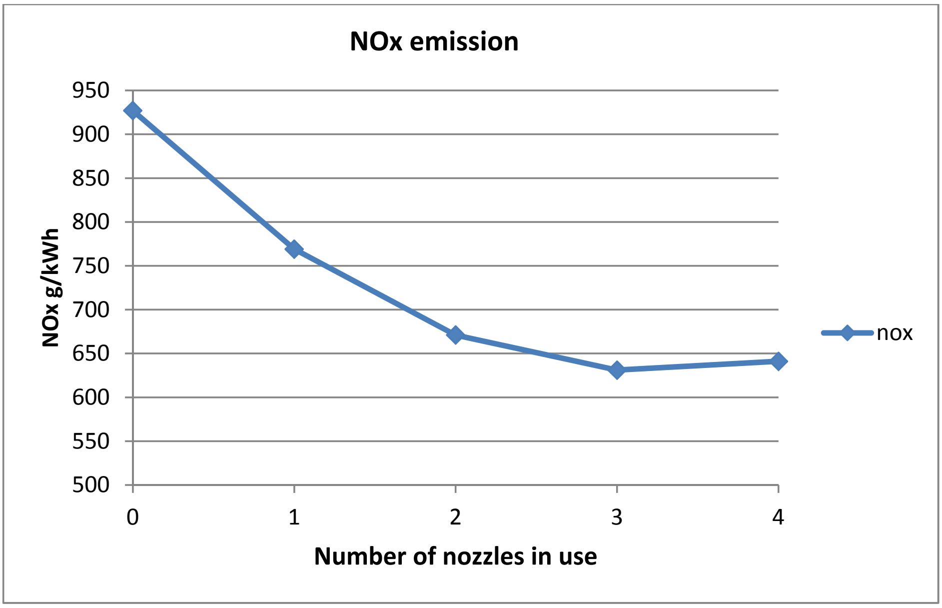

Figure A–8–1. The NO_x emission graph.

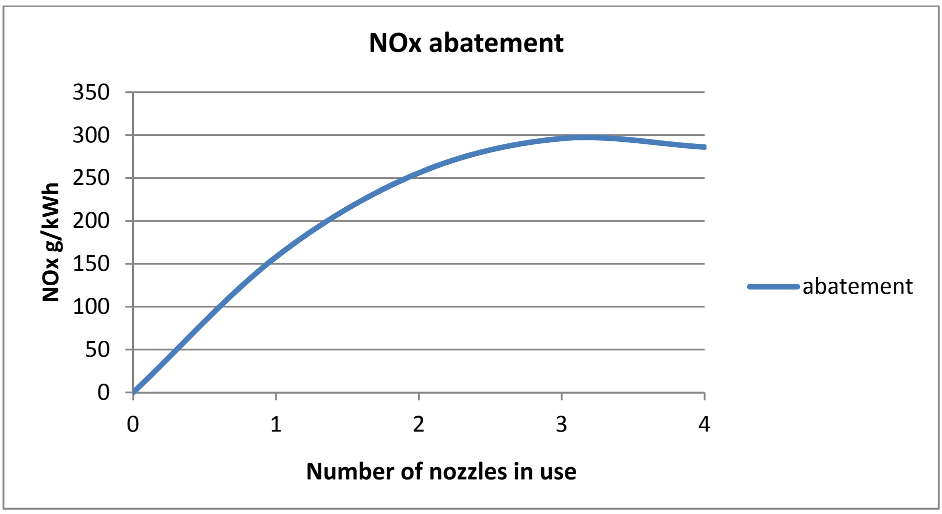

Figure A–8–2. The NO_x abatement graph.

The measured NO_x emission levels may indicate a malfunction in nozzle number four. As is clear from the graphs, the fourth nozzle has no effect.

APPENDIX 9. Sample from the measurement log

Date/Time	CO	CO2	Corr NO	Corr NOx	Corr SO2	NO	NOx	O2	SO2	Nox2	Eng. load	Speed	(A)NOx	Urea	(B)NOx
	ppm	vol%	ppm	ppm	ppm	ppm	ppm	vol%	ppm		%	k	10avrg	l/min	10avrg
14:30	95.58333	6.315	0	390.25	196.25	0	216.25	12.68667	109.3333	1198.55	85	19	225.7917	92	1207.244
14:40	94.5	6.32	0	411	198.4167	0	227.75	12.69	110.75	1188.81	85	19	233.4833	92	1194.787
14:50	94.41667	6.313333	0	427.0833	201.5	0	236.5	12.70083	112.0833	1148.51	85	18.5	233.3583	93	1164.474
15:00	94.16667	6.31	0	415	203.4167	0	229.25	12.71333	113	1128.5	85	19	231.4833	96	1140.428
15:10	93.75	6.334167	0	418.5	205.5	0	231.5833	12.70417	114.1667	1128.5	85	19	233.7333	96	1126.525
15:20	95.66667	6.320833	0	474.9167	207	0	262.75	12.7	115.0833	1098.74	86	19	247.8667	88	1112.462
15:30	95	6.345	0	481.5	207	0	266.9167	12.68917	115.3333	1109.01	84	19	244.65	91	1105.956
15:40	93.75	6.349167	0	465.75	208.25	0	258.4167	12.68417	116.0833	1098.74	85	19	248.2083	90	1102.848
15:50	129.5833	6.675	0	426.75	213.5	0	249	12.24167	125.6667	1068.72	85	19	183.175	87	1003.931
16:00	245.5833	2.714167	0	1456.833	263.8333	0	372.5	17.16167	67.66667	398.728	35	7	230	0	819.7105
16:10	235.3333	5.584167	0	446.0833	160.4167	0	220.1667	13.59917	79.66667	728.718	40	7	618.0417	14	671.4374
16:20	214.8333	7.045833	0	344.0833	213	0	212.25	11.73833	132.5	1138.51	85	15	181.9	88	953.9708
17:40	91.58333	6.363333	0	512.3333	213.8333	0	285.5833	12.64333	120	1051.33	50	12	262.1	87	1066.741
17:50	181	6.560833	0	41.33333	210.0833	0	23.66667	12.43	120.75	578.603	45	8	224.1583	0	992.9992
18:00	155	6.720833	0	2030.667	146.5833	0	1194.25	12.17667	86.75	1048.17	85	13	781.6667	0	818.0501
18:10	240.3333	4.554167	0	1107.667	170.1667	0	447.1667	15.1025	67.25	698.959	36	8.5	324.9583	0	894.6613
18:20	318.3333	7.348333	0	1658.667	164.4167	0	1073.333	11.24917	107.4167	1078.2	85	13	849.8333	0	798.588
18:30	216.8333	7.070833	0	223.6667	202.0833	0	137.75	11.75167	125.4167	1118.49	85	14.5	612.1417	66	1091.022
18:40	188.0833	6.931667	0	193.0833	208.6667	0	116.25	11.94583	126.6667	1068.45	73	15	187.7417	81	1096.711
18:50	218.4167	4.893333	0	1601.583	156.8333	0	698.75	14.455	68.83333	808.517	43	9	407.4667	0	880.5458
19:00	442.3333	1.27	0	925.5	180.5	0	123.5	19.00333	24.08333	149.589	30	9	566.5583	0	542.6016
19:10	89.83333	0.101667	0	83.58333	11.91667	0	11.16667	20.7125	4.666667	30.2864		0	71.10833	0	
21:00										1178.27	85	15	649.6417	86	968.2713
21:10	163.0833	6.835833	0	284.4167	205.25	0	168.4167	12.11417	122.5	1158.26	60	15	124.4767	76	966.3228
21:20	208.9167	4.128333	0	774.8333	181.0833	0	296.0833	15.59167	64.91667	818.261	42	8	58.46667	0	940.3529
21:30	240	6.056667	0	1767.917	147.75	0	939.5	13.0275	78.91667	878.307	42	8.5	845.8667	0	854.3676
21:40	92.33333	6.365	0	421.0833	212.75	0	232.3333	12.73167	118	1155.63	85	14	488.7833	92	1146.065
21:50	249.25	5.785	0	1714.333	159.8333	0	867.0833	13.415	81.16667	834.853	80	13	493.1917	0	803.2491
22:00	93.08333	6.3825	0	487.75	213.25	0	268.4167	12.74667	118.0833	1148.51	85	14	572.25	89	1146.273
22:10	94.5	6.3425	0	433.6667	215.5833	0	238.75	12.74833	119.4167	1118.76	85	16	248.9333	87	1137.558
22:20	345.4167	7.163333	0	189.25	197.1667	0	116.75	11.745	122.5	988.392	54	12	118.3167	35	1021.706
22:30	270.9167	6.869167	0	174.9167	183.9167	0	103.5833	12.10833	109.8333	978.184	53	11.5	66.45	40	991.2355
22:40	294.8333	6.9925	0	172.1667	179.0833	0	103.75	11.95333	108.5833	958.895	52	12	100.1667	39	971.6157
22:50	310.25	7.318333	0	243.5833	176.3333	0	153.5	11.57667	111.3333	1048.17	75	12	123.6167	40	967.9018

APPENDIX 10. Consumption log and calculations (1/3)

Data originating from the emission report, sea trial report, engine test reports and bunker certificates. Abatement is calculated in Table 2. within the document. Consumption values are from the log of the case study vessel. Sources and calculations are listed below table A10–2.

Table A10–1. Excerpt from the vessel's consumables log.

	Main engine operating hours				Total oil consumption m^3	Total urea consumption m^3
	1	2	3	4		
Day 1	20	19	2	11	52.81	3.8
Day 2	20	19	2	13	53.94	3.6
Day 3	21	20	2	13	53.86	3.6
Day 4	20	19	2	13	55.97	3.8
Day 5	21	21	4	10	53.05	4.6
Day 6	20	20	4	10	53.55	5.7
Day 7	15	18	10	14	55.25	3.4
Day 8	20	19	9	8	54.59	4.2
Subtotal	158	157	38	96		
Total	439				433	33

Table A10–2. Calculated and sampled values.

Variable	*Value*	*Note*
Energy content	41.17 MJ / kg	1
Fuel density	980.7 kg / m^3	1
Fuel sulphur content	0.44 %	1
Engine running time during sampled 8 days	439 hours	2
Fuel consumption, 8-day sample period	433 m^3	2
Fuel consumption in kilograms, 8-day sample period	423 840 kg	2
Urea consumption, 8-day sample period	33 m^3	2
Running hours, 8-day sample period	439 h	2
Running hours, 365 days	20 030 h	3
Specific fuel oil consumption	205.6 g / kWh	4
Sampled average load	72.1 %	5
Wärtsilä 16V32LN nominal power	6560 kW	6
Sampled average power	4730 kW	7
Energy consumption, 365 days	95 000 MWh	8
Average NO_x reduction	7.7 g / kWh	9
Total urea consumption, 365 days	1500 m^3	10
Average urea consumption	17.5 g / kWh	11
Average urea consumption in hour	0.172 m^3	12
Total reduction, one year	732 tons	13
Total cost, 365 days	580 000 €	14
Average cost for 1 ton reduction	800 €	15
Average Urea / NO_x ratio	44 %	16

APPENDIX 10. Consumption log and calculations (3/3)

1. Source: Bunker certificate, fuel analysis report.
2. Source: Vessel onboard log.
3. Calculation: Running hours.
   $$\frac{439\ hours}{8\ days} * 365\ days\ = 20\ 030\ hours$$
4. Source: Manufacturer test report.
5. Taken and calculated from notes taken onboard during the measurement run.
   Calculated from 246 samples. The average load during engine run is 72.077 % ≈ 72.1 %.
6. Source: manufacturer installation sheet.
7. Calculation: Main engine average power.
   $$72.1\ \% *\ 6560\ kW = 4730\ kW$$
8. Calculation: Energy consumption in one year.
   $$20030 \frac{h}{a} * 4730\ kW \approx 95\ 000 \frac{MWh}{a}$$
9. Source: Emission report, summary in Appendix 1.
10. Calculation: Bunkered urea volume.
    $$33\ \ \frac{m^3}{8\ days} * 365\ days \approx 1500\ m^3$$
11. Calculation: Urea consumption per kilowatt-hour.
    $$\frac{1500\ \frac{m^3}{a} * 1110\ \frac{kg}{m^3}}{95\ 000\ 000 \frac{kW}{a}} \approx 0.00175\ \frac{kg}{kW}\ \approx 17.5\ \frac{g}{kWh}$$
    Density of 40 % urea/water solution is $1110\ \frac{kg}{m^3}$
12. Calculation: Urea consumption in one hour.
    $$\frac{33\ m^3}{8\ days * 24 \frac{hours}{day}}\ \approx 0.172 \frac{m3}{hour}$$
13. Calculation: NO_x reduction amount in one year.
    $$0.0077 \frac{kg}{kWh} *\ \ 95\ 000\ 000\ kWh \approx 731\ 500\ kg\ \ \approx 732\ tons$$
14. Values form Table 1.
15. Calculation: Cost of one ton of reduced NO_x.
    $$\frac{580\ \frac{k€}{a}}{732 \frac{tons}{a}}\ \approx 800 \frac{€}{ton}$$
16. Calculation: Ratio of reduced NO_x mass / urea mass. $\frac{732\ 000 \frac{kg}{a}}{1500\ \frac{m3}{a} * 1110 \frac{kg}{m3}}\ \ \approx 0.44 = 44\ \%$

PUBLICATIONS OF KYMENLAAKSO UNIVERSITY OF APPLIED SCIENCES.

SERIES B Research and Reports

B 1 Markku Huhtinen & al.:
Laivadieselien päästöjen vähentäminen olemassa olevissa laivoissa [1997].

B 2 Ulla Pietilä, Markku Puustelli:
An Empiral Study on Chinese Finnish Buying Behaviour of International Brands [1997].

B 3 Markku Huhtinen & al.:
Merenkulkualan ympäristönsuojelun koulutustarve Suomessa [1997].

B 4 Tuulia Paane-Tiainen:
Kohti oppijakeskeisyyttä. Oppijan ja opettajan välisen ohjaavan toiminnan hahmottamista [1997].

B 5 Markku Huhtinen & al.:
Laivadieselien päästöjä vähentävien puhdistuslaitteiden tuotteistaminen [1998].

B 6 Ari Siekkinen:
Kotkan alueen kasvihuonepäästöt [1998]. Myynti: Kotkan Energia.

B 7 Risto Korhonen, Mika Määttänen:
Veturidieseleiden ominaispäästöjen selvittäminen [1999].

B 8 Johanna Hasu, Juhani Turtiainen:
Terveysalan karusellikoulutusten toteutuksen ja vaikuttavuuden arviointi [1999].

B 9 Hilkka Dufva, Mervi Luhtanen, Johanna Hasu:
Kymenlaakson väestön hyvinvoinnin tila, selvitys Kymenlaakson väestön hyvinvointiin liittyvistä tekijöistä [2001].

B 10 Timo Esko, Sami Uoti:
Tutkimussopimusopas [2002].

B 11 Arjaterttu Hintsala:
Mies sosiaali- ja terveydenhuollon ammattilaisena – minunko ammattini? [2002].

B 12 Päivi Mäenpää, Toini Nurminen:
Ohjatun harjoittelun oppimisympäristöt ammatillisen kehittymisen edistäjinä – ARVI-projekti 1999-2002 [2003], 2 p. [2005] .

B 13 Frank Hering:
Ehdotus Kymenlaakson ammattikorkeakoulun kestävän kehityksen ohjelmaksi [2003].

B 14 Hilkka Dufva, Raija Liukkonen
Sosiaali- ja terveysalan yrittäjyys Kaakkois-Suomessa. Selvitys Kaakkois-Suomen sosiaali- ja terveysalan palveluyrittäjyyden nykytilasta ja tulevaisuuden näkymistä [2003].

B 15 Eija Anttalainen:
Ykköskuski: kuljettajien koulutustarveselvitys [2003].

B 16 Jyrki Ahola, Tero Keva:
Kymenlaakson hyvinvointistrategia 2003 –2010 [2003], 2 p. [2003].

B 17 Ulla Pietilä, Markku Puustelli:
Paradise in Bahrain [2003].

B 18 Elina Petro:
Straightway 1996—2003. Kansainvälinen transitoreitin markkinointi [2003].

B 19 Anne Kainlauri, Marita Melkko:
Kymenlaakson maaseudun hyvinvointipalvelut - näkökulmia maaseudun arkeen sekä mahdollisuuksia ja malleja hyvinvointipalvelujen kehittämiseen [2005].

B 20 Anja Härkönen, Tuomo Paakkonen, Tuija Suikkanen-Malin, Pasi Tulkki:
Yrittäjyyskasvatus sosiaalialalla [2005]. 2. p. [2006]

B 21 Kai Koski (toim.):
Kannattava yritys ei menetä parhaita asiakkaitaan. PK-yritysten liiketoiminnan kehittäminen osana perusopetusta [2005]

B 22 Paula Posio, Teemu Saarelainen:
Käytettävyyden huomioon ottaminen Kaakkois-Suomen ICT-yritysten tuotekehityksessä [2005]

B 23 Eeva-Liisa Frilander-Paavilainen, Elina Kantola, Eeva Suuronen:
Keski-ikäisten naisten sepelvaltimotaudin riskitekijät, elämäntavat ja ohjaus sairaalassa [2006]

B 24 Johanna Erkamo & al.:
Oppimisen iloa, verkostojen solmimista ja toimivia toteutuksia yrittäjämäisessä oppimisympäristössä [2006]

B 25 Johanna Erkamo & al.:
Luovat sattumat ja avoin yhteistyö ikäihmisten iloksi [2006]

B 26 Hanna Liikanen, Annukka Niemi:
Kotihoidon liikkuvaa tietojenkäsittelyä kehittämässä [2006]

B 27 Päivi Mäenpää
Kaakkois-Suomen ensihoidon kehittämisstrategia vuoteen 2010 [2006]

B 28 Anneli Airola, Arja-Tuulikki Wilén (toim.):
Hyvinvointialan tutkimus- ja kehittämistoiminta Kymenlaakson ammattikorkeakoulussa [2006]

B 29 Arja-Tuulikki Wilén:
Sosiaalipäivystys – kehittämishankkeen prosessievaluaatio [2006].

B 30 Arja Sinkko (toim.):
Kestävä kehitys Suomen ammattikorkeakouluissa – SUDENET-verkostohanke [2007].

B 31 Eeva-Liisa Frilander-Paavilainen, Mirja Nurmi, Leena Wäre (toim.):
Kymenlaakson ammattikorkeakoulu Etelä-Suomen Alkoholiohjelman kuntakumppanuudessa [2007].

B 32 Erkki Hämäläinen & Mari Simonen:
Siperian radan tariffikorotusten vaikutus konttiliikenteeseen 2006 [2007].

B 33 Eeva-Liisa Frilander-Paavilainen & Mirja Nurmi:
Tulevaisuuteen suuntaava tutkiva ja kehittävä oppiminen avoimissa ammattikorkeakoulun oppimisympäristöissä [2007].

B 34 Erkki Hämäläinen & Eugene Korovyakovsky:
Survey of the Logistic Factors in the TSR-Railway Operation - "What TSR-Station Masters Think about the Trans-Siberian?" [2007].

B 35 Arja Sinkko:
Kymenlaakson hyvinvoinnin tutkimus- ja kehittämiskeskus (HYTKES) 2000-2007. Vaikuttavuuden arviointi [2007].

B 36 Erkki Hämäläinen & Eugene Korovyakovsky:
Logistics Centres in St Petersburg, Russia: Current status and prospects [2007].

B 37 Hilkka Dufva & Anneli Airola (toim.):
Kymenlaakson hyvinvointistrategia 2007 - 2015 [2007].

B 38 Anja Härkönen:
Turvallista elämää Pohjois-Kymenlaaksossa? Raportti Kouvolan seudun asukkaiden kokemasta turvallisuudesta [2007].

B 39 Heidi Nousiainen:
Stuuva-tietokanta satamien työturvallisuustyön työkaluna [2007].

B 40 Tuula Kivilaakso:
Kymenlaaksolainen veneenveistoperinne: venemestareita ja mestarillisia veneitä [2007].

B 41 Elena Timukhina, Erkki Hämäläinen, Soma Biswas-Kauppinen:
Logistic Centres in Yekaterinburg: Transport - logistics infrastructure of Ural Region [2007].

B 42 Heidi Kokkonen:
Kouvola muuttajan silmin. Perheiden asuinpaikan valintaan vaikuttavia tekijöitä [2007].

B 43 Jouni Laine, Suvi-Tuuli Lappalainen, Pia Paukku:
Kaakkois-Suomen satamasidonnaisten yritysten koulutustarveselvitys [2007].

B 44 Alexey V. Rezer & Erkki Hämäläinen:
Logistic Centres in Moscow: Transport, operators and logistics infrastructure in the Moscow Region [2007].

B 45 Arja-Tuulikki Wilén:
Hyvä vanhusten hoidon tulevaisuus. Raportti tutkimuksesta Kotkansaaren sairaalassa 2007 [2007].

B 46 Harri Ala-Uotila, Eeva-Liisa Frilander-Paavilainen, Ari Lindeman, Pasi Tulkki (toim.):
Oppimisympäristöistä innovaatioiden ekosysteemiin [2007].

B 47 Elena Timukhina, Erkki Hämäläinen, Soma Biswas-Kauppinen:
Railway Shunting Yard Services in a Dry-Port. Analysis of the railway shunting yards in Sverdlovsk-Russia and Kouvola-Finland [2008].

B 48 Arja-Tuulikki Wilén:
Kymenlaakson muisti- ja dementiaverkosto. Hankkeen arviointiraportti [2008].

B 49 Hilkka Dufva, Anneli Airola (toim.):
Puukuidun uudet mahdollisuudet terveyden- ja sairaanhoidossa. TerveysSellu-hanke. [2008].

B 50 Samu Urpalainen:
3D-voimalaitossimulaattori. Hankkeen loppuraportti. [2008].

B 51 Harri Ala-Uotila, Eeva-Liisa Frilander-Paavilainen, Ari Lindeman (toim.):
Yrittäjämäisen toiminnan oppiminen Kymenlaaksossa [2008].

B 52 Peter Zashev, Peeter Vahtra:
Opportunities and strategies for Finnish companies in the Saint Petersburg and Leningrad region automobile cluster [2009].

B 53 Jari Handelberg, Juhani Talvela:
Logistiikka-alan pk-yritykset versus globaalit suuroperaattorit [2009].

B 54 Jorma Rytkönen, Tommy Ulmanen:
Katsaus intermodaalikuljetusten käsitteisiin [2009].

B 55 Eeva-Liisa Frilander-Paavilainen:
Lasten ja nuorten terveys- ja tapakäyttäytyminen Etelä-Kymenlaakson kunnissa [2009].

B 56 Kirsi Rouhiainen:
Viisasten kiveä etsimässä: miksi tradenomiopiskelija jättää opintonsa kesken? Opintojen keskeyttämisen syiden selvitys Kymenlaakson ammattikorkeakoulun liiketalouden osaamisalalla vuonna 2008 [2010].

B 57 Lauri Korppas - Esa Rika - Eeva-Liisa Kauhanen:
eReseptin tuomat muutokset reseptiprosessiin [2010].

B 58 Kari Stenman, Rajka Ivanis, Juhani Talvela, Juhani Heikkinen:
Logistiikka & ICT Suomessa ja Venäjällä [2010].

B 59 Mikael Björk, Tarmo Ahvenainen:
Kielelliset käytänteet Kymenlaakson alueen logistiikkayrityksissä [2010].

B 60 Anni Mättö:
Kyläläisten metsävarojen käyttö ja suhtautuminen metsien häviämiseen Mzuzun alueella Malawissa [2010].

B 61 Hilkka Dufva, Juhani Pekkola:
Turvallisuusjohtaminen moniammatillisissa viranomaisverkostoissa [2010].

B 62 Kari Stenman, Juhani Talvela, Lea Värtö:
Toiminnanohjausjärjestelmä Kymenlaakson keskussairaalan välinehuoltoon [2010].

B 63 Tommy Ulmanen, Jorma Rytkönen:
Intermodaalikuljetuksiin vaikuttavat häiriöt Kotkan ja Haminan satamissa [2010].

B 64 Mirva Salokorpi, Jorma Rytkönen
Turvallisuus ja turvallisuusjohtamisjärjestelmät satamissa [2010].

B 65 Soili Nysten-Haarala, Katri Pynnöniemi (eds.):
Russia and Europe: From mental images to business practices [2010].

B 66 Mirva Salokorpi, Jorma Rytkönen:
Turvallisuusjohtamisen parhaita käytäntöjä merenkulkijoille ja satamille [2010].

B 67 Hannu Boren, Marko Viinikainen, Ilkka Paajanen, Viivi Etholen:
Puutuotteiden ja -rakenteiden kemiallinen suojaus ja suojauksen markkinapotentiaali [2011].

B 68 Tommy Ulmanen, Jorma Rytkönen, Taina Lepistö:
Tavaravirtojen kasvusta ja häiriötekijöistä aiheutuvat haasteet satamien intermodaalijärjestelmälle [2011].

B 69 Juhani Pekkola, Sari Engelhardt, Jussi Hänninen, Olli Lehtonen, Pirjo Ojala:
2,6 Kestävä kansakunta. Elinvoimainen 200-vuotias Suomi [2011].

B 70 Tommy Ulmanen:
Strategisen osaamisen johtaminen satama-alueen Seveso-laitoksissa [2011].

B 71 Arja Sinkko:
LCCE-mallin käyttöönotto tekniikan ja liikenteen toimialalla – ensiaskeleina tuotteistaminen ja sidosryhmäyhteistyön kehittäminen [2012].

B 72 Markku Nikkanen:
Observations on Responsibility – with Special reference to Intermodal Freight Transport Networks [2012].

B 73 Terhi Suuronen:
Yrityksen arvon määrittäminen yrityskauppatilanteessa [2012].

B 74 Hanna Kuninkaanniemi, Pekka Malvela, Marja-Leena Saarinen (toim.):
Research Publication 2012 [2012].

B 75 Tuomo Väärä, Reeta Stöd, Hannu Boren:
Moderni painekyllästys ja uusien puutuotteiden testaus aidossa, rakennetussa ympäristössä. Jatkohankkeen loppuraportti [2012].

B 76 Ilmari Larjavaara
Vaikutustapojen monimuotoisuus B-to-B-markkinoinnissa Venäjällä - lahjukset osana liiketoimintakulttuuria [2012].

B 77 Anne Fransas, Enni Nieminen, Mirva Salokorpi, Jorma Rytkönen:
Maritime safety and security. Literature review [2012].

B 78 Juhani Pekkola, Olli Lehtonen, Sanna Haavisto:
Kymenlaakson hyvinvointibarometri 2012. Kymenlaakson hyvinvoinnin kehityssuuntia viranhaltijoiden, luottamushenkilöiden ja ammattilaisten arvioimana [2012].

B 79 Auli Jungner (toim.):
Sosionomin (AMK) osaamisen työelämälähtöinen vahvistaminen. Ongelmaperustaisen oppimisen jalkauttaminen työelämäyhteistyöhön [2012].

B 80 Mikko Mylläri, Jouni-Juhani Häkkinen:
Biokaasun liikennekäyttö Kymenlaaksossa [2012].

B 81 Riitta Leviäkangas (toim.):
Yhteiskuntavastuuraportti 2011 [2012].

B 82 Riitta Leviäkangas (ed.):
Annual Responsibility Report 2011 [2012].

B 83 Juhani Heikkinen, Janne Mikkala, Niko Jurvanen
Satamayhteisön PCS-järjestelmän pilotointi Kaakkois-Suomessa. Mobiilisatama-projektin työpaketit WP4 ja WP5, loppuraportti 2012 [2012].

B 84 Tuomo Väärä, Hannu Boren
Puun modifiointiklusteri. Loppuraportti 2012 [2012].

B 85 Tiina Kirvesniemi
Tieto ja tiedon luominen päiväkotityön arjessa [2012].

B 86 Sari Kiviharju, Anne Jääsmaa
KV-hanketoiminnan osaamisen ja kehittämistarpeiden kartoitus - Kyselyn tulokset [2012].

B 87 Satu Hoikka, Liisa Korpivaara
Työhyvinvointia yrittäjälle - yrittäjien kokemuksia Hyvinvointikoulusta ja näkemyksiä yrittäjän työhyvinvointia parantavista keinoista [2012].

B 88 Sanna Haavisto, Saara Eskola, Sami-Sepppo Ovaska
Kopteri-hankkeen loppuraportti [2013].

B 89 Marja-Liisa Neuvonen-Rauhala, Pekka Malvela, Heta Vilén, Oona Sahlberg (toim.)
Sidos 2013 - Katsaus kansainvälisen liiketoiminnan ja kulttuurin toimialan työelämäläheisyyteen [2013].

B 90 Minna Söderqvist
Asiakaskeskeistä kansainvälistymistä Kymenlaakson ammattikorkeakoulun yritysyhteistyössä [2013].

B 91 Sari Engelhardt, Marja-Leena Selenius, Juhani Pekkola
Hyvän tuulen palvelu. Kotkan terveyskioski hyvinvoinnin edistäjänä - Kotkan terveyskioskikokeilun arviointi 2011-2012 [2013].

B 92 Anne Fransas, Enni Nieminen, Mirva Salokorpi
Maritime security and safety threats – Study in the Baltic Sea area [2013].

B 93 Valdemar Kallunki (toim.)
Elämässä on lupa tavoitella onnea: Nuorten aikuisten koettu hyvinvointi, syrjäytyminen ja osallisuus Kaakkois-Suomessa ja Luoteis-Venäjällä. Voi hyvin nuori -hankkeen loppuraportti. [2013].

B 94 Hanna Kuninkaanniemi, Pekka Malvela, Marja-Leena Saarinen (toim.):
Research Publication 2013 [2013].

B 95 Arja Sinkko (toim.): **Tekniikan ja liikenteen toimialan LCCE-toiminta Yritysyhteistyönä käytännössä: logistiikan opiskelijoiden ”24 tunnin ponnistus”[2013].**

B 96 Markku Nikkanen:
Notes & Tones on Aspects of Aesthetics in Studying Harmony and Disharmony: A Dialectical Examination [2013].

B 97 Riitta Leviäkangas (toim.):
Yhteiskuntavastuuraportti 2012 [2013].

B 98 Mervi Nurminen, Teija Suoknuuti, Riina Mylläri (toim.)
Sidos 2013, NELI North European Logistics Institute - Katsaus logistiikan kehitysohjelman tuloksiin[2013].