NTNU – Trondheim
Norwegian University of
Science and Technology

Cost-Efficient Emission Control Area Compliancy

Stine Madsen
Tina Charlotte Olsson

Marine Technology
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Supervisor: Bjørn Egil Asbjørnslett, IMT

Norwegian University of Science and Technology
Department of Marine Technology

Abstract

The overall aim of this case study is to find the most cost-effective strategy for complying with the IMO's MARPOL Convention Regulation 13 & 14 in the Baltic Sea Emission Control Areas (ECAs) in the period from 2015 to 2035. The alternative compliance strategies considered are:

- Scenario 0: Use Marine Gas Oil (MGO), with 0.1% sulphur, to comply with the sulphur requirements, no other abatement measures installed, but an assumed NO_x-taxation applies;
- Scenario 1: Use Heavy Fuel Oil (HFO), with 2.7% sulphur, and add scrubber and SCR to reduce SO_x and NO_x emissions, respectively;
- Scenario 2: Use Marine Gas Oil (MGO), with 0.1% sulphur, together with SCR; and
- Scenario 3: Use Liquefied Natural Gas (LNG), single fuel or dual fuel.

The following route is established: Helsinki - Zeebrugge - Antwerp - St. Petersburg - Kotka - Helsinki. The total distance for the roundtrip is 3,654 nm. 48 roundtrips are completed every year. Based on the specific fuel consumption for the engine and the sulphur content in the fuel, the sulphur emission factor for each scenario is calculated. The amount of SO_x emitted from the ship is found by summarizing the product of the engine load, the engine size, the ships estimated time at sea and the emission factor. The NO_x emission limits for the ship engines in relation to their rated engine speed given in revolutions per minute. The NO_x emission factor is assumed to be constant at 55 kg NO_x per ton fuel.

Investment analyses are performed for a ship type both as new builds and as retrofitted. Operational costs include: fuel costs, lubricating oil costs, maintenance and repair/replacement costs, environmental taxation and educational costs (where applicable), among others. The cost and emission results for each scenario are listed in Table 1.

Scenario 0 is chosen as reference point based on the fact that it has the lowest investment cost among the scenarios. The cost-effectiveness ratio (CER) relative Scenario 0 is found from the following formula:

$$ICER = \frac{\Delta Costs}{\Delta Emissions} \tag{1}$$

The following conclusions are drawn from the cost-effectiveness analysis:

- The scrubber in combination with SCR is a favored compliance strategy for IMO's requirements, both for new builds and retrofits. It has the lowest fuel costs (HFO prices are low and stable) and the lowest present value of total costs among the scenarios outlined.

Table 1: The cost and emission results for each scenario

		Scenario:				
		0	**1**	**2**	**3 (DF)**	**3 (SF)**
Fuel Consumption	[tons/year]	13,825	13,825	13,825	15,088	15,386
SO_x Emission Factor	[g/kWh]	0.35	9.50	0.35	-	-
SO_x Emissions	[tons]	553	747	553	0	0
NO_x Emissions	[tons]	15,208	2,661	2,661	1,521	1,217
Total Capital Costs, NB	[MEUR]	0	3.25	1.49	28.30	28.86
Present Value of Costs, NB	[MEUR]	208	126	199	194	198
Total Capital Costs, R	[MEUR]	0	4.55	2.09	39.62	40.40
Present Value of Costs, R	[MEUR]	193	128	199	206	209

- Having an engine running on MGO is not considered cost-effective. MGO prices are high, and are expected to increase even more. NO_x abatement technologies are needed in addition.
- LNG is a cost-effective solution, and it is the most environmentally friendly alternative. Retrofitting vessels to run on LNG, however, is expensive. The LNG dual fuel technology is a flexible solution, and makes it more economic for the ship to trade outside the ECAs.
- The cost comparison between the different scenarios depends largely on the future development of fuel prices.
- Modal shift to either rail or road could be a consequence.

Preface

The work of our Master Thesis has been carried out at the Department of Marine Technology during the spring of 2012. The thesis is a requirement for completing the Master of Science degree in Marine Technology at the Norwegian University of Science and Technology (NTNU). The topic of the project is *Cost-Efficient Emission Control Area Compliancy.* The report counts for 30 credits, or 100% of a semester's work load.

Our Master Thesis is an extension of our Project Thesis, carried out during the fall of 2011. The main purpose of our study has been to compare potential solutions able to meet the requirements set by the International Maritime Organization (IMO) regarding emissions of SO_x and NO_x from shipping in the Emission Control Areas (ECAs) from 2015.

The fundamental work has been time-consuming. We have independently created a model in Excel for the analysis. The calculations have been compared, and the figures have been confirmed to match. A general explanation for the model is provided in Part III - Case Study, and Part IV - Cost-Effectiveness Analysis. The worksheets are electronically attached.

It has been a challenging yet educational 5^{th} year. The project and master thesis work has provided us with greater understanding on how to approach new subjects, and how a pre-study is built up. We have learned that it takes time to become familiar with new topics, and we have seen the importance of proper time disposal and good planning in the initial phase. All in all, it has been a valuable experience, and we hope that we have succeeded.

We would like to thank our supervisor Professor Bjørn Egil Asbjørnslett, for guidance and constructive feedback with this report. We would also like to thank Martin Wold, consultant at DNV Environment & Energy Efficiency, who has provided us with essential information, both for our Project Thesis and during this semester.

Stine Madsen

Tina Charlotte Olsson

Trondheim, 9th Jun, 2012

Scope of Work

NTNU Trondheim
Norwegian University of Science and Technology
Department of Marine Technology

MASTER THESIS IN MARINE TECHNOLOGY
SPRING 2012
For stud.techn
Stine Madsen & Tina Charlotte Olsson
Cost efficient Emission Control Area Compliancy

Background

The global LNG (Liquefied Natural Gas) short sea trading fleet is now counting 22 ships, of which 21 are currently operating in Norway. It took 10 years to get the first 22 LNG fuelled ships floating. The confirmed orderbook is very soon the same size as the existing fleet, so in less than three years time were certain we will see the next 22 LNG fuelled ships in Norway alone. So far the LNG ship fuel development outside Norway has been limited though. However, the international maritime industry is under pressure to reduce the environmental impact from shipping. The new ECA (Emission Control Area) requirements have just brought LNG to the shipowners attention, and have made LNG a very real option to consider for every single newbuild for operation in these areas.

Areas where a significant share of the world ship trade takes place have been designated as Emission Control Areas (ECA) by the IMO. For ships sailing in these areas, stricter requirements for emissions to air apply, as described in MARPOL Annex VI. These requirements are being implemented gradually and will have full force in 2015 and 2016, leaving shipowners a limited number of options for modifications to their ships if they want to continue trading here. Shipowners operating in Europe and Northern America are currently asking themselves the following question: What is the most cost-efficient way to comply with these new requirements?

Objective

The objective with this project will be to assess a specific ship, ship type or fleet with ECA operation and determine the most cost-efficient way of complying with IMOs requirements. Sensitivity analysis to assess the robustness of the conclusion will be a key task. A model which can be used to assess the effect of key parameters such as remaining life time, share of ECA operation and fuel prices is to be developed.

The project thesis part of these objectives should have particular focus on establishing a structured overview of state of art within this area of knowledge.

The project thesis shall in addition define alternative scope of work for the following master thesis.

Tasks

The candidate is recommended to cover the following parts in the project thesis:

1. General description of relevant background information.
2. Establish scenarios for a shipping company on how to comply with the emission regulations.
3. Develop a model, quantify costs and emissions and conduct a cost-effectiveness analysis.
4. Discuss the results from the analysis, define a solution for the ship owner, and give a final conclusion.

General

In the thesis the candidate shall present his personal contribution to the resolution of a problem within the scope of the thesis work.

Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

The candidate should utilize the existing possibilities for obtaining relevant literature.

The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work. The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

Deliverable

- The thesis shall be submitted in two (2) copies:
- Signed by the candidate
- The text defining the scope included
- In bound volume(s)

- Drawings and/or computer prints that cannot be bound should be organized in a separate folder.
- The bound volume shall be accompanied by a CD or DVD containing the written thesis in Word or PDF format. In case computer programs have been made as part of the thesis work, the source code shall be included. In case of experimental work, the experimental results shall be included in a suitable electronic format.

Bjørn Egil Asbjørnslett
Professor/Responsible Advisor

Martin Wold
Company Contact at Det Norske Veritas

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List of Abbreviations

CBA	Cost-Benefit Analysis
CEA	Cost-Effectiveness Analysis
CER	Cost-Effectiveness Ratio
COPD	Chronic Obstructive Pulmonary Disease
ECA	Emission Control Area
EGCS	Exhaust Gas Cleaning System
EGR	Exhaust Gas Recirculation
GHG	Green House Gases
HAM	Humid Air Motor
HFO	Heavy Fuel Oil
ICEA	Incremental Cost-Effectiveness Analysis
ICER	Incremental Cost-Effectiveness Ratio
IFO	Intermediate Fuel Oil
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
LSHFO	Low Sulphur Heavy Fuel Oil
MARPOL	Marine Pollution - The International Convention for the Prevention of Pollution from Ships
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
NB	New Build
NO_x	Nitrogen Oxides
PM	Particulate Matter
PVC	Present Value of Costs
R	Retrofit
RFO	Residual Fuel Oil
SCR	Selective Catalytic Reduction
SECA	Sulphur Emission Control Area
SO_x	Sulphur Oxides
VOC	Volatile Organic Compounds

1. Introduction

Shipping is one of the most efficient and environmentally friendly modes of transportation, referring to good per unit. Still, ships are the largest single emission source for pollution to air in the transport sector. The projected growth in shipping due to an expansion in trade is causing an increased environmental concern. Pollutants, such as CO_2, NO_x and SO_x, cause environmental effects that have impact on climate change, local air quality and consequently on nature and health.

The International Maritime Organization (IMO) ship pollution rules are contained in the "International Convention on the Prevention of Pollution from Ships". In October 2008 the IMO adopted a set of amendments to Annex VI of the MARPOL 73/78, which set more stringent limits on SO_x and NO_x emissions from ship exhaust. These new regulations require that the sulphur content in fuel oil be reduced to 0.1% by January 2015. Furthermore, from January 2016, there will be a subsequent requirement for reducing nitrogen oxides from new ships. The North and Baltic Sea areas have been declared special Emission Control Areas (ECAs) by the IMO, and are the most affected areas by the new regulations.

There is a great reduction potential in emissions from shipping. To improve air quality, a different number of measures can be applied to reduce SO_x and NO_x emissions; switch to low sulphur fuels, using heavy fuel oil with add-on-technologies, engine modifications, switch to LNG operation, etc. Regardless of which compliance strategy a ship owner chooses, the owner faces increased costs if he wants to continue trading in the ECAs. This study aims towards determining the most cost-effective solution for complying with the IMO's strict requirements by looking into different scenarios.

Structure of Thesis

The report consists of four main parts. Part I describes emissions from shipping with a focus on the impact on air quality. The regulations that are relevant in this context are presented, and a short description of the abatement measures that can be applied to meet the regulations.

Part II provides an overview of the theoretical framework used in the case study. The cost-effectiveness analysis is summarized in ten key steps.

Part III presents a straight-forward approach for estimating energy use and emissions of SO_x and NO_x. A detailed description of each scenario is provided, and how the different costs are quantified.

Finally in Part IV, the cost-effectiveness analysis is outlined, including a sensitivity analysis, conclusions and further work.

Part I

Background Information

2. Emission from Shipping

Today, the world fleet, consisting of more than 100,000 ships, carries more than 80% of international trade (measured in metric tons). Even though maritime transportation is one of the most efficient and environmentally friendly ways of transportation, large ships, like the oil tankers, carry potentially dangerous cargoes and are a high source of pollution, Helcom (2011). The environmental impact of shipping can be segmented in five categories:

- SO_x and PM emissions;
- NO_x emissions;
- CO_2 emissions;
- Chemical release from vessels; and
- Waste generation (solid as well as liquid waste).

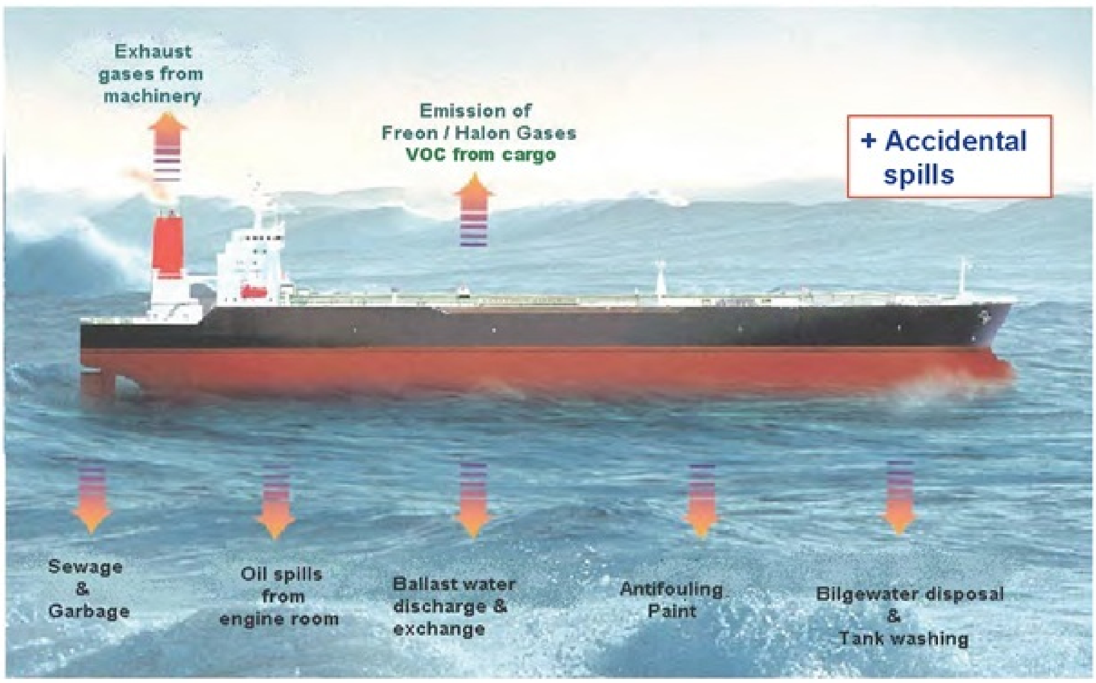


Figure 2.1: Emissions/discharges from shipping to air and sea, Lindstad (2011).

In the following chapter the focus will be on the shipping sectors' effect on air emissions and pre-dominantly on local pollution related to NO_x and SO_x emissions.

2.1 Emissions to Air

Shipping represents a significant contribution to the global anthropogenic emissions, Lindstad (2011):

- 3% CO_2 (3.3% all shipping, 2.7% international shipping)
- 4-9% SO_x
- 10-15% NO_x

In a diesel engine, chemical energy from the fuel is converted into mechanical power. The fuel is injected under high pressure into the cylinder where it evaporates and mixes with air. During the combustion process exhaust gases are formed. The presence of these exhaust gases has local and global impacts. Impacts on local (or regional) air quality are mainly linked to pollutants such as PM, NO_x, and sulphur, while the GHGs (e.g. CO_2) have a global impact on climate, Miola et al. (2010).

2.1.1 SO_x

Sulphur emissions are proportional to the sulphur content in the fuel. Emissions of SO_x (SO_2 and SO_3) are formed during the combustion process of fossil fuels and condense when released into the atmosphere. During the combustion process sulphur dioxide is formed, but also a small fraction (typically 5%) of sulphur dioxide oxidizes to sulphur trioxide, Wahlström et al. (2006):

$$S + O_2 \rightarrow SO_2 \tag{2.1}$$

$$2SO_2 + O_2 \rightarrow 2SO_3 \tag{2.2}$$

When the gas is cooled, sulphur trioxide will react with any available water to form sulphuric acid, which can lead to corrosion:

$$SO_3 + H_2O \rightarrow H_2SO_4 \tag{2.3}$$

Sulphur emissions harm the environment through acidification as well as human health, particularly around coastal areas and ports, Helcom (2011).

Environmental Impacts

Sulphur dioxide is the primary air pollutant causing acidification in many areas. Acid rain occurs when the sulphur dioxide reacts in the atmosphere with water, oxygen, and other chemicals to form various acidic compounds. Sulphur compounds emitted from ships can cause acid depositions that can be detrimental to the natural environment (lakes, rivers, soils, fauna and flora).

Human Health Impacts

SO_x is a toxic gas, which is directly harmful to human health. Some of the negative effects SO_x have on human health are, Gray (2008):

- Irritation of eyes, nose, throat, damage to lungs when inhaled;
- Acute and chronic asthma;
- Bronchitis and emphysema; and
- Lung cancer.

2.1.2 NO_x

NO_x comprises of both nitric oxide (NO) and nitrogen dioxide (NO_2). Emissions of NO_x are formed from the endothermic reaction of nitrogen and oxygen gases in the air during combustion of fossil fuels, especially at high temperatures. Key sources of nitrogen oxide include: nonroad mobile sources (e.g. marine, railroads, diesel equipment) and onroad mobile sources (e.g. trucks, cars and motorcycles); power plants; cement and concrete installations; other industrial processes, Gray (2008).

Environmental Impacts

NO_x emissions from ships cause acidic depositions that can be detrimental to the natural environment. Nitrogen oxide can also contribute to eutrophication, disrupting ecosystems, creating harmful algae blooms in coastal waters and increasing nitrate concentrations in groundwater. These effects can have serious consequences for both plant life and water fauna, Shipping (2012).

Health Impacts

Short-term exposure to high NO_x concentrations may lead to changes in airway responsiveness and lung function, while long term exposure may lead to increased respiratory infection and may cause alterations in the lung. Depending on different NO_2 concentrations in the air, nitrogen dioxide pollution effects may be summarized as follows, Gray (2008):

- Increased incidence of respiratory illness;
- Increased airway resistance (due to inflammation);
- Damage to lung tissue;
- Chronic obstructive pulmonary disease, or COPD (narrowing of the airways);
- Emphysema (as part of COPD);
- Pulmonary edema (accumulation of excessive fluid in the lungs); and
- Infant and cardiovascular death.

2.1.3 PM

Particulate matter (PM) emissions consist of three fractions: soot (dry carbon particles), soluble organic fraction (hydrocarbons absorbed and condensed on carbon particles) and hydrated sulphuric acid (SO_4), Wahlström et al. (2006). The formation of particulate matter is depended on the efficiency and completeness of the combustion process, the amount of hydrocarbons, sulphur and ash in the fuel and the amount of lubricating oil used.

2.2 The IMO Sets Standards

The International Maritime Organization (IMO) is an agency of the United Nations which has formed to promote maritime safety. The IMO ship pollution rules are contained in the "International Convention on the Prevention of Pollution from Ships", known as MARPOL 73/78. In October 2008 the IMO adopted a set of amendments to Annex VI of the MARPOL Convention - "Regulations for the Prevention of Air Pollution from Ships". This annex sets limits on NO_x and SO_x emissions from ship exhaust, and other harmful emissions from ships. For NO_x emissions, the limits have been set as a function of nominal engine rotational speed, while to mitigate the SO_x emissions, the sulphur content of marine fuels is being regularly restricted in terms of percentage sulphur by weight.

The revised MARPOL Annex VI operates with two geographical definitions: Global and Emission Control Area (ECA). The IMO emission standards are commonly referred to as Tier I, II and III, DNV (2010).

2.3 Emission Control Area

Stricter emission requirements, than the global requirements, are regulated in specifically designated geographical areas. An emission control area can be designated for SO_x and PM, or NO_x, or all three types of emissions from ships. The introduction of ECAs is an attempt to address these aspects and reduce the environmental footprint of the shipping industry, DMA (2011a).

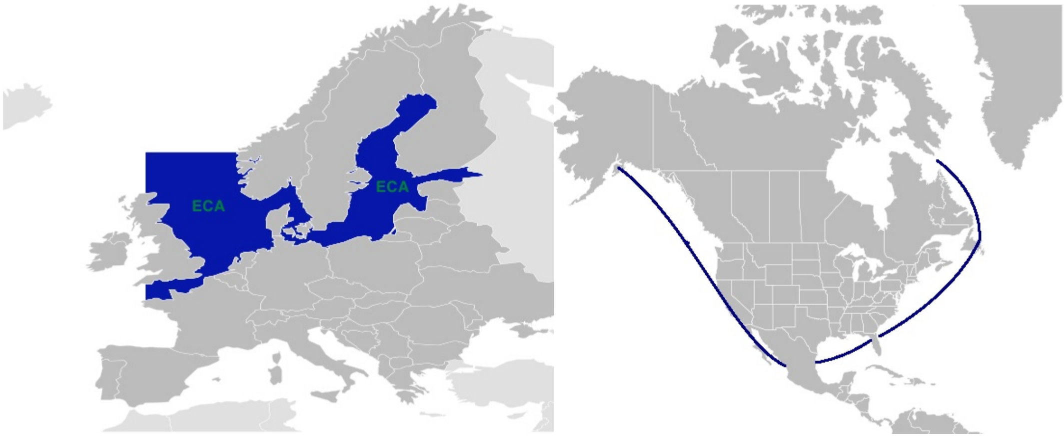
Existing emission control areas include:

- The Baltic Sea (for NO_x; entered into force on 19^{th} May 2006);
- The North Sea, which also includes the English Channel (for SO_x; entered into force in 22^{nd} November 2007); and
- The North American ECA, including most of the US and Canadian coast (for NO_x and SO_x; entered into force in 2011).

2.4 Regulation 14 - Sulphur Oxides (SO_x) and Particulate Matter

As of 2012, the maximum permitted sulphur content in marine fuel is cut to 3.5% by weight and, as of 2020, to 0.5% by weight. An overview of the availability of low-sulphur fuel on the international market shall be carried out in 2018. If it is then demonstrated that the fuel supply is too limited, the limit of 0.5% by weight shall become effective on 1^{st} January 2025, IMO (2008).

Within the Baltic Sea, the North Sea and the English Channel, the limit value of 1.0% by weight is applicable at present. This limit is to be changed on 1^{st} January 2015 to 0.1% by weight.



(a) (b)

Figure 2.2: Emission Control Area in (a) the Baltic Sea and the North Sea, and in (b) North America, DNV (2010).

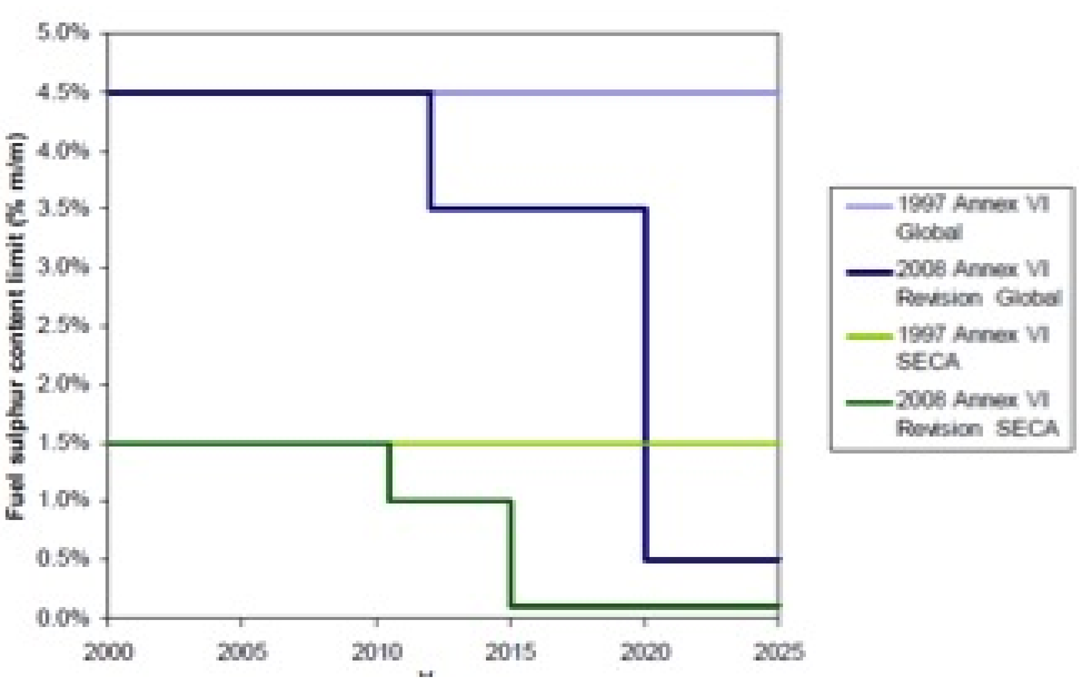


Figure 2.3: Revised MARPOL Annex VI - Fuel Sulphur Limits, Entec (2010).

2.5 Regulation 13 - Nitrogen Oxides (NO_x)

The Tier I standards were defined in the 1997 version of Annex VI, while the Tier II and III standards were introduced by Annex VI amendments adopted in October 2008, IMO (2008).

Tier I

For diesel engines installed on ships constructed from 1st January 2000 and prior to 1st January 2011 allowable emissions of total weighted NO_x depending on engine speed, n, are:

1. 17.0 g/kWh when n is less than 130 rpm;
2. $45 \times n^{(-0.2)}$ g/kWh when n is 130 or more but less than 2000 rpm;
3. 9.8 g/kWh when n is 2000 rpm or more.

Tier II

For diesel engines installed on ships constructed on or after 1st January 2011 allowable emissions of total weighted NO_x depending on engine speed, n, are:

1. 14.4 g/kWh when n is less than 130 rpm;
2. $44 \times n^{(-0.23)}$ g/kWh when n is 130 or more but less than 2000 rpm;
3. 7.7 g/kWh when n is 2000 rpm or more.

Tier III

Ships constructed on or after 1st January 2016 will have additional limitations when operating in an ECA. For Tier III ships operating in the NO_x ECAs the allowable emissions of total weighted NO_x depending on engine speed, n, are:

1. 3.4 g/kWh when n is 130 rpm;(*)
2. $9 \times n^{(-0.2)}$ g/kWh when n is 130 or more but less than 2000 rpm;
3. 2.0 g/kWh when n is 2000 rpm or more.

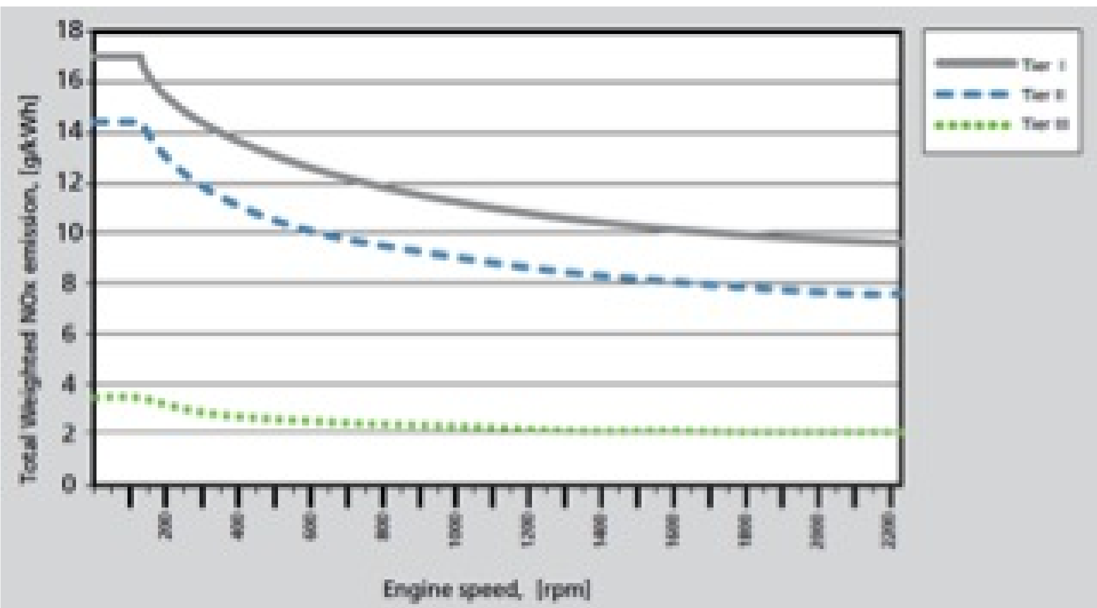


Figure 2.4: The allowable NO_x emission from diesel engines, DNV (2011).

Tier III limits will not apply to engines installed on a ship with a length of less than 24 meters when it is designed and used solely for recreational purposes. Nor will it apply for an engine installed on a ship with a combined nameplate diesel engine propulsion power of less than 750 kW if it is demonstrated that the ship cannot comply with the standards set forth in paragraph 5.1.1 (*) of this regulation because of design or construction limitations of the ship.

3. How to Comply with the Regulations

3.1 What is an abatement measure?

The emission reduction measures can be divided into four main categories, DNV (2010):

- Technical measures generally aim at either reducing the power requirement to the engines or improving fuel efficiency. These measures often have relatively high investment costs, but on the other hand emission reductions are also relatively high. In general, retrofitting is more expensive compared to applying technical measures in the design and building phase of a ship. More efficient engines and devices to trap exhaust emissions are examples of such measures.
- Alternative fuels and power sources can replace conventional fossil fuels in order to reduce emissions to air. Operational costs may rise due to the premium price for the alternative fuels or power source.
- Operational measures with a focus on reducing emissions to air mostly include changes in the operation and the maintenance of the ship. The measures generally have low investment needs and moderate operating costs, and are closely related to management and training programs. Many operational measures are attractive for purely economic reasons.
- Structural measures impose changes that are characterized by two or more counterparts in shipping working together to increase efficiency and reduce emissions by altering the way in which they interact.

3.2 Identification of Abatement Measures

There are several technically and economically feasible techniques to reduce shipping emissions. The methods to reduce sulphur dioxide emissions are the switch from fuel with a high sulphur content to low sulphur ones, and/or the introduction of exhaust gas scrubbing technology. For nitrogen oxides the most promising method is selective catalytic reduction systems, but internal engine modifications, water injection techniques or exhaust gas recirculation are also applicable. Particulate matter emissions are reduced with the sulphur dioxide reduction measures.

Some of the most promising emission techniques are listed in Table 3.1. The engine manufacturers use different combinations of these methods to meet the IMO's emission limits. In Chapter 4 a more detailed presentation of the various emission reduction methods used in the case study, are described.

Table 3.1: Pollutant reduced from abatement measure

Abatement Measure	NO_x	SO_x
Engine Modifications		
Internal engine adjustments	X	
Water injection	X	
Selective non-catalytic reduction	X	
Exhaust gas recirculation	X	
After-Treatment Technologies		
Scrubber		X
Selective catalytic reduction	X	
Particulate filters		X
Alternative Fuels and Energy Sources		
Low-sulphur fuels		X
Liquefied natural gas	X	X
New Ship Design and Modification		
Optimizing ships' design and operation	X	X
New ship design	X	X

4. Abatement Measures

This chapter describes what seems to be the most utilized NO_x and SO_x reducing measures: the exhaust gas cleaning scrubber, the selective catalytic reduction and fuel switch to either MGO or LNG. The technologies "promise" to reduce emissions so that the IMO's requirements for 2015 and 2016 are met. The technologies described are those used in the cost-effectiveness analysis in Part IV. The other abatement measures listed in Chapter 3 are not included.

4.1 Selective Catalytic Reduction (SCR)

The most promising methods for reducing nitrogen oxide emissions are internal engine modifications, water injection techniques, exhaust gas recirculation (EGR) and selective catalytic reduction (SCR), Wahlström et al. (2006). The different technologies can be used independently or in combination. At present selective catalytic reduction is the only efficient way to reach the NO_x reduction needed for the IMO Tier III rules, apart from burning LNG, Wärtsilä (2011a).

General Description

A selective catalytic reduction system consists of a urea tank, a pumping unit and a control system for dosing of urea in addition to the SCR unit itself. The SCR system reduces the level of nitrogen oxide in the exhaust gas from the engine by means of catalyst elements and a reducing agent. In the process a urea water solution is added to the exhaust gas stream. The water in the urea solution evaporates as the solution is injected into the exhaust gas. Exhaust gas NO_x emissions react with the ammonia at a catalytic surface, and are thereafter transformed into the end products: molecular nitrogen, N_2, and water, H_2O, Wärtsilä (2011a). The main chemical reaction of this process is:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \tag{4.1}$$

The high temperature also induces thermal decomposition of the urea, $(NH_2)2CO$, into ammonia, NH_3, and carbon dioxide, CO_2. The temperature of the SCR process is generally between 250 and 500^oC. In order to reach sufficient reaction rates, the minimum temperature is typically 300-450^oC for fuel qualities with sulphur content of max. 1%, Wärtsilä (2011a).

The efficiency of the catalytic reduction depends on a number of factors, including the dosage of the reducing agent, the amount of catalyst element and the exhaust gas temperature. Normally, a NO_x reduction level of 90% can be reached, Wärtsilä (2011a). To reach a 90% NO_x reduction, approximately 1.5 liter of urea is needed per kg NO_x. The efficiency of the reactor is directly linked to the amount of urea added to the exhaust gas flow. The system is capable of reducing all NO_x in the exhaust gas flow, but not without a high risk of "ammonia slip" through the system.

The system works independent of the combustion process: selective catalytic reduction is an "add-on" exhaust treatment system, it does not interfere with the basic engine design and allows

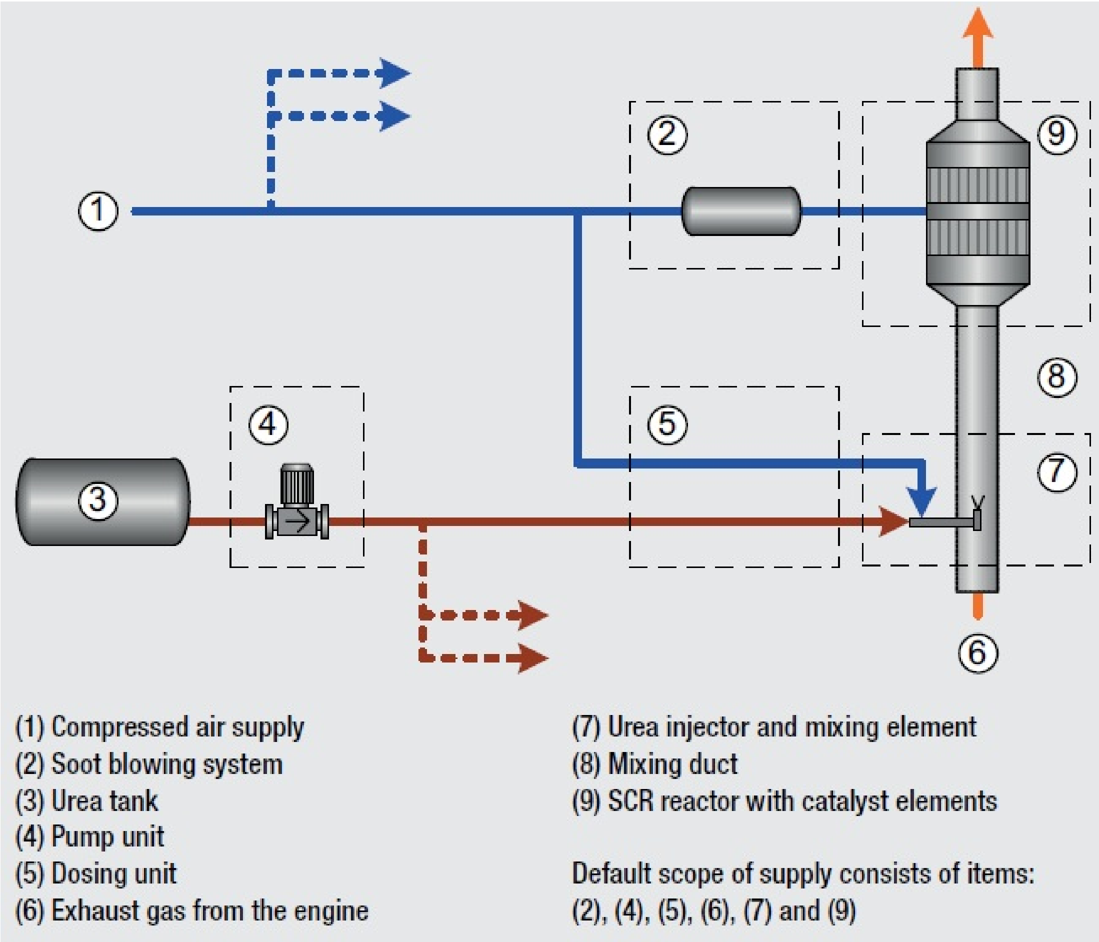


Figure 4.1: Flow diagram of the SCR system, Wärtsilä (2011a).

a free choice of engine manufacturer, Entec (2005). In order to avoid the loss of exhaust gas temperature and to achieve high efficiency, it is recommended to install the SCR as close to the engine as possible. Due to the frequent changes in engine load, the temperature will vary. For engines operating on low loads, the exhaust gas temperature tends to drop below the lower operational limit, and the urea injection is stopped. This might influence the amount of NO_x emitted.

Degrading

The two main concerns when it comes to catalyst degrading is fatigue of and deposits in the ceramic material. Once installed in the exhaust system, the catalyst is exposed to both mechanical and thermal stress, Selås (2010). The lifetime of the catalyst depends on various parameters such as temperature, fuel and lube oil quality. In order to maintain the NO_x reduction capacity of the SCR system, the catalyst elements should be replaced at regular intervals, Wärtsilä (2011a). Typically, the catalytic elements in the reactor will need to be replaced every 4-5 years. It is not necessary to exchange the entire catalytic material after this period. The catalysts are arranged in a layered system, which allows for damaged catalysts to be identified, removed and exchanged. The other components need periodical inspection and maintenance. Depending on the quality of fuel, lube oil, the operation profile, and the maintenance routines, the lifetime of the catalyst may vary, IACCSEA2012 (2012).

4.2 Scrubber

There are several configurations of marine exhaust gas cleaning systems (often referred to as scrubbers) that remove sulphur oxides from ships engines. Four technologies are known to be utilized, EMSA (2010):

1. The seawater scrubber (open loop scrubber);
2. The freshwater scrubber (closed loop scrubber);
3. The hybrid technology (a combination of 1 and 2); and
4. The CSNO_x system (which targets not only sulphur oxides but also nitrogen oxides and CO_2).

In the following, the two most common scrubbing technologies, the freshwater scrubber and the seawater scrubber, are described. Only the freshwater scrubber has been considered in the cost-effectiveness analysis in Part IV.

General Description

Exhaust gas cleaning systems remove the harmful substances directly from the fuel gas and allow the use of regular fuels. The majority of the systems have three basic components:

- A vessel which enables the exhaust stream from an engine to be intimately mixed with water;
- A treatment plant to remove pollutants from the wash water after the scrubbing process; and
- Sludge handling facilities; sludge removed by the wash water treatment plant must be retained onboard for disposal ashore and cannot be burned in the ship's incinerators.

The system is designed for maximum sulphur content in the fuel of 3.5%. The SO_x reduction efficiency can be as high as 97.15%, corresponding to a reduction of fuel sulphur content from 3.5% to 0.1%, Wärtsilä (2011c). The PM content in the exhaust gases is also significantly reduced (40-80%). The system may be a closed loop exhaust scrubber (freshwater scrubber) or an open loop exhaust scrubber (seawater scrubber).

The fresh water scrubber uses fresh water and sodium hydroxide, NaOH, to remove SO_x from the exhaust gas stream on ships. The washing solution is pumped from the process tank through a system cooler to the scrubber. From the scrubber the washing solution returns to the process tanks by gravity, Miola et al. (2010).

In an open loop scrubber, the water is taken from the sea, used for scrubbing, treated and discharged back to the sea. The natural alkaline characteristic of the seawater makes it possible to neutralize the sulphuric products from the engine exhaust gas.

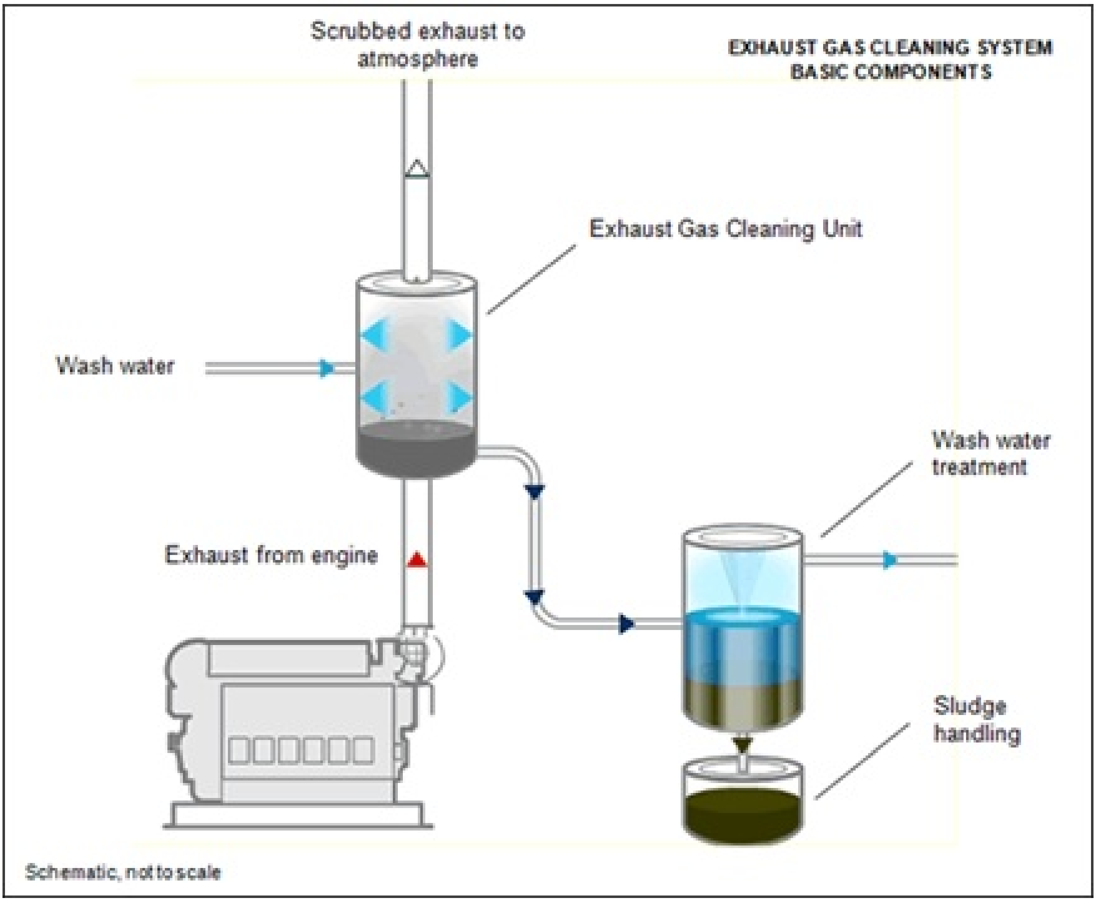


Figure 4.2: Basic components of a scrubber, *ECSA* (2012).

Sludge generated in the scrubber process is similar to engine room sludge. The composition of the sludge is mainly hydrocarbons, soot and metals, Wärtsilä (2011c). Generally, the amount of sulphur discharged seems to be insignificant compared to the quantity of sulphate that sea-water naturally contains. However, Annex VI of the MARPOL Convention forbids discharging scrubber waste into the water, Miola et al. (2010). The scrubber sludge has to be stored on board prior to final delivery to a shore reception facility. The sludge can be stored in the same tank as other engine room sludge.

The fresh water scrubber and the sea water scrubber are suitable for both new builds and retrofit installations, EMSA (2010). The advantage of using the fresh water scrubber is that it opens the possibility to use the scrubbing technology in sea areas where the natural alkalinity of the sea water is not sufficient to react on its own with the sulphur. The disadvantages of the scrubber system include the required capital investments together with the scrubber waste. Also, scrubbers need to be certified and controlled by Port Authorities' which increase the administrative work. Scrubbers also occupy space and in some cases cargo capacity might be reduced, DMA (2011c).

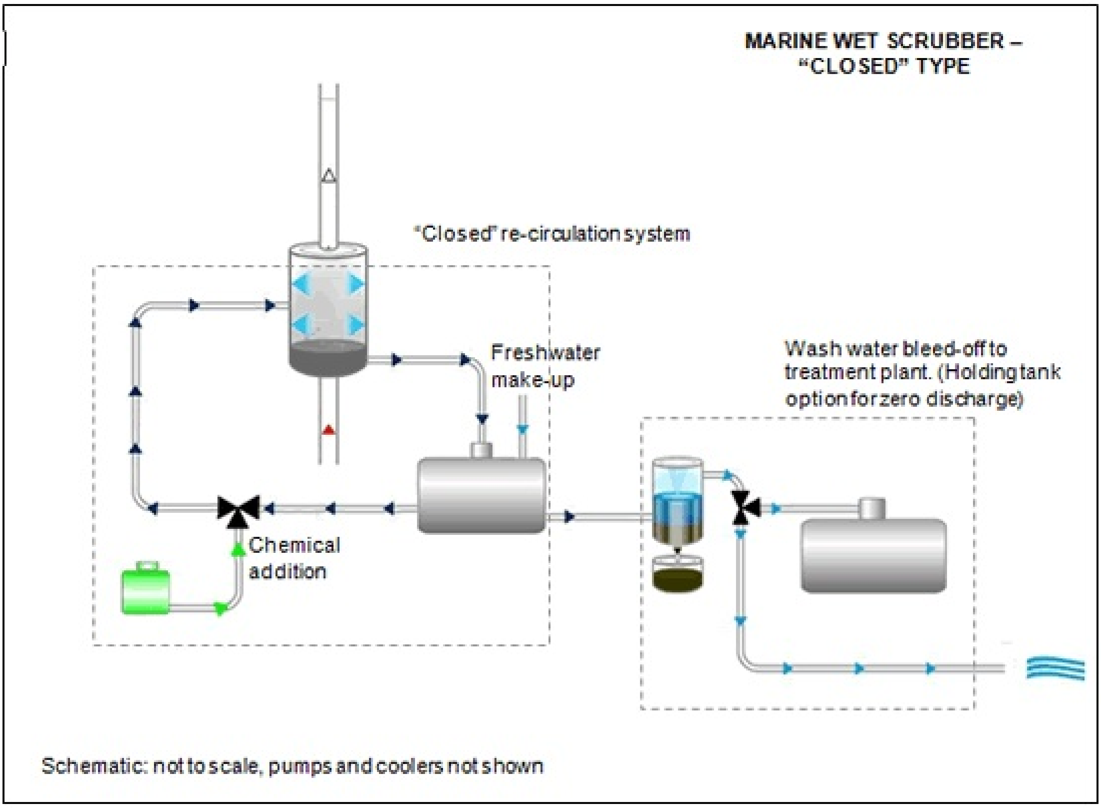


Figure 4.3: Fresh water scrubber, *ECSA* (2012).

Degrading

Maintenance of the scrubber system comprises generic maintenance tasks of individual pieces of equipment (such as valves and actuators, pumps, electric motors, heat exchanger, tanks, etc.). The scrubber unit is equipped with maintenance hatches for periodical inspection of the internals and spray nozzles. In normal and operating conditions maintenance service work to the scrubber unit is minimal, Wärtsilä (2011c).

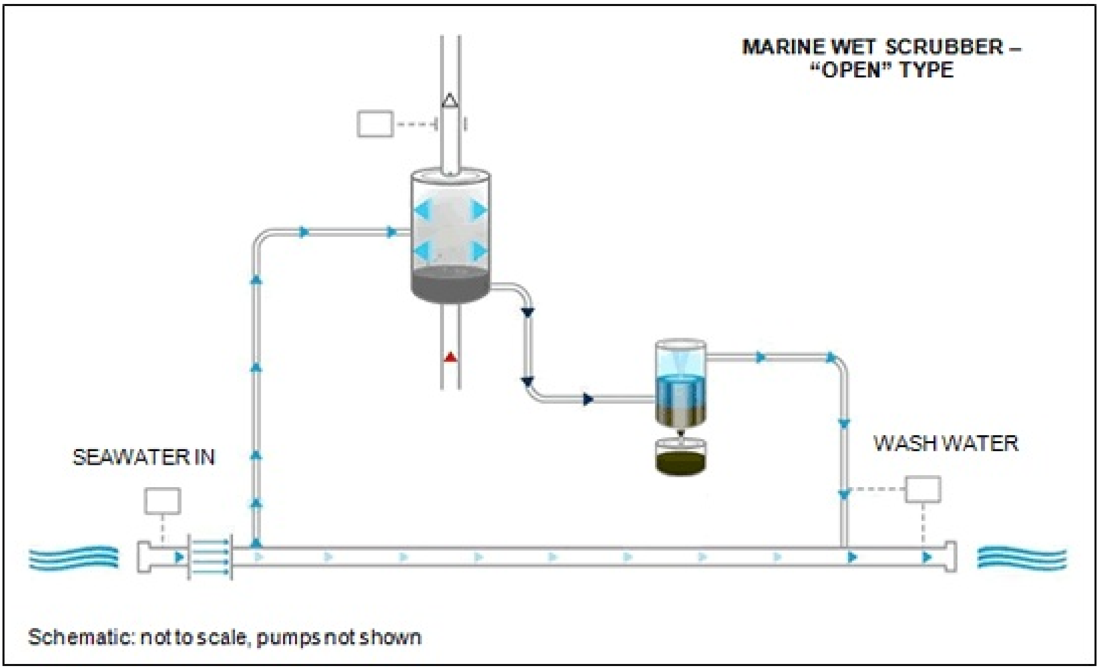


Figure 4.4: Seawater scrubber, *ECSA* (2012).

4.3 Switch to Low Sulphur Fuel

Marine Gas Oil (MGO) has no problem with sulphur emissions, and the switch from high sulphur fuels to low sulphur fuels is possibly the simplest option to comply with the IMO's fuel sulphur requirements.

Table 4.1: Sulphur contents of various fuel types, DMA (2011c)

Fuel Type	Description	Sulphur Content [%]
IFO 380 cSt	Residual fuel containing distillate fuels	3.5
LSHFO 380 cSt	Residual fuel with low sulphur content	1 or 1.5
MDO	Heavier distillate containing some residual components	0.2
MGO	Distillate only	0.1 - 0.005
LNG	Liquefied natural gas	0

Switching to low sulphur fuels only require minor engine modifications in case of retrofitting, Wahlström et al. (2006). Low sulphur fuel has higher quality than regular HFO and because of that it makes the engine run smoother and causes less wear on the accompanied machinery components. The risk of operating problem is reduced, and less maintenance is needed. The operating costs, however, can be significantly higher due to the high fuel costs as described in Chapter 9 - Marine Fuels.

4.4 LNG

Another abatement measure is to fuel the ship with LNG. Natural gas is the cleanest form of fossil fuels available and it produces less emissions and pollutants than either coal or oil. Engines that operate on LNG have, compared to diesel engines, approximately 25% less CO_2 emissions, 90% less NO_x and zero SO_x emissions, Einang (2010). The most dominant component is methane with some ethane and small amounts of heavy hydrocarbons, DNV (2010). Emissions on non-combusted methane (a potent GHG) is a problem when operating outside the optimised load-spectra, DNV (2010).

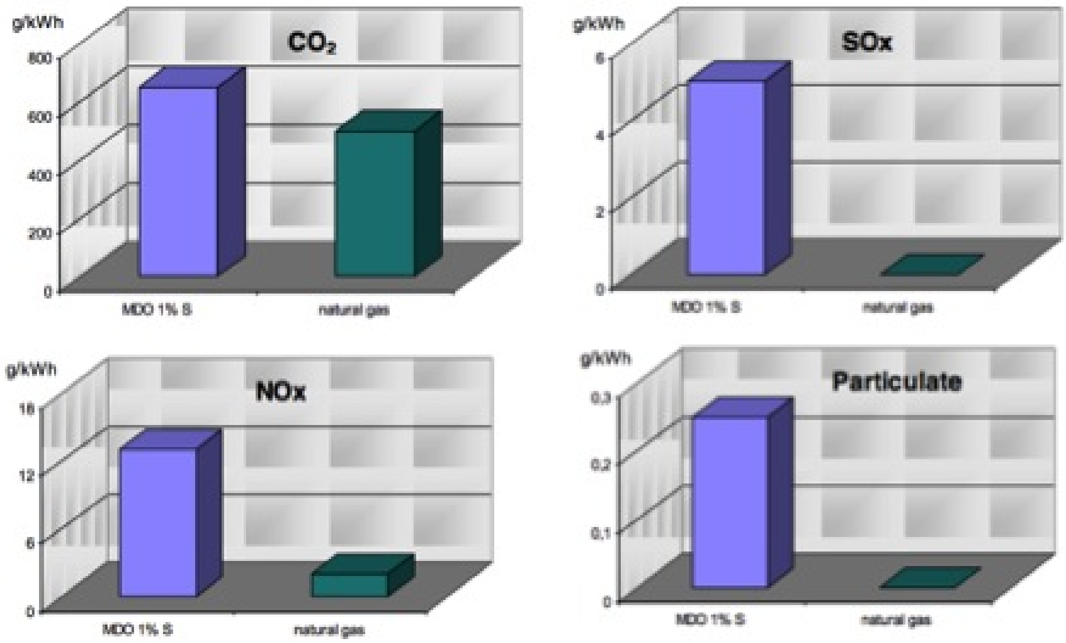


Figure 4.5: Bergen engines: MDO versus natural gas emissions, Rolls-Royce (2011).

LNG is a fossil methane gas stored as liquid at -162^oC, DNV (2010). Since LNG is cryogenic (very low temperature), the tanks must undergo a special cool down procedure with liquid nitrogen before they can be filled wth LNG for the first time. An amount of the natural gas need to remain in the tanks and kept cold at all times, TGA (2011a).

Natural gas has a high auto ignition temperature and therefore needs an additional ignition source, i.e. a pilot fuel, to ignite in combustion engines. LNG is lighter than air and has a narrow flammability interval. It can be combusted in two stroke engines or in four stroke Otto engines, DMA (2011c).

The energy density of natural gas depends on the gas makeup, which gives a spesific fuel consumption unit of [kJ/kWh] instead of the regular mass based unit, TGA (2011a).

A distinction between the gas engines is usually made between pure gas engines and gas engines that can run on different types of fuels (dual fuel), DNV (2010).

Dual Fuel Engine

The fuel switch from liquid to gas operation mode can be made on operators command. This operation flexibility is a real advantage with the dual fuel system. The natural gas is supplied to the engine through a gas valve unit, where the gas is filtered and gas pressure is controlled. When running the engine in gas mode, the air/gas mixture is ignited with a small quantity of MDO pilot fuel, Wärtsilä (2012a).

The natural gas is supplied to the engine through a gas valve unit. The gas is first filtered to ensure a clean supply. On the engine, the gas is supplied through large pipes running along the engine, Wärtsilä (2012a).

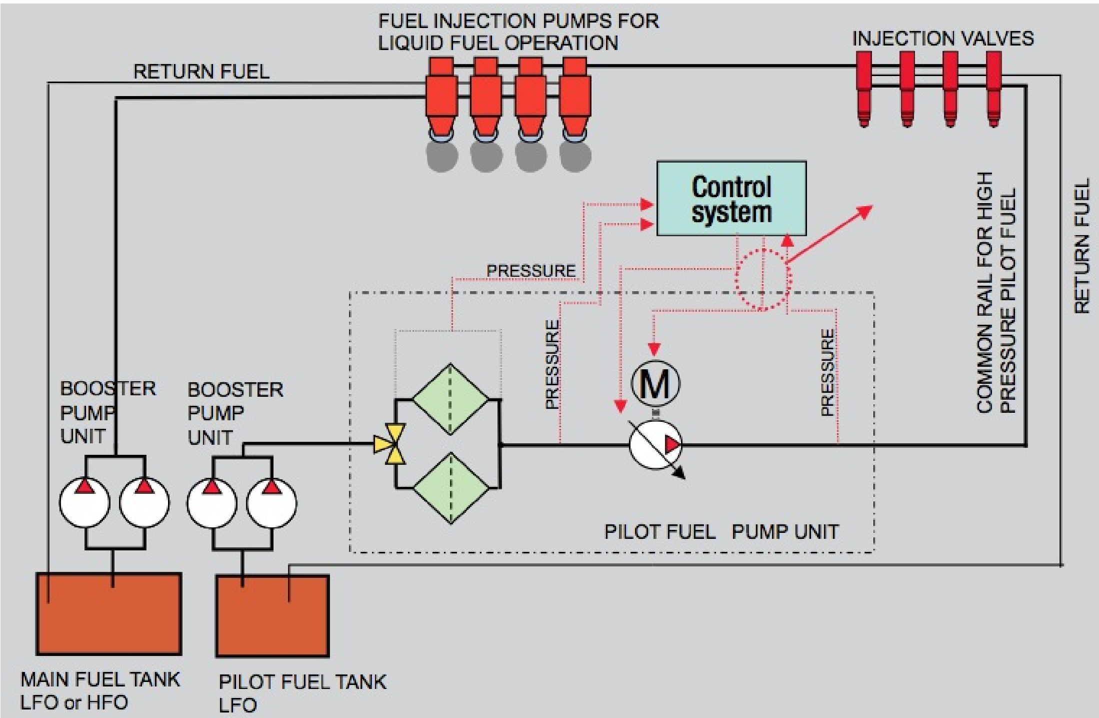


Figure 4.6: The gas supply of an Wärtsilä dual fuel engine, Wärtsilä (2012a).

Single Fuel Engine

A lean-burn engine operates on the Otto cycle with mixture compression and an external ignition source. A rich gas/air mix in a precombustion chamber is ignited and forms a strong ignition source for the very lean mixture in the cylinder for knock-free combustion. This allows for an increased cylinder power and gives high efficiency and reduced emissions, Rolls-Royce (2011).

Gas Fuel System

The gas fuel system includes the LNG storage tanks, gas vaporization equipment, gas distribution system, and bunkering system. The general gas system arrangement will vary from dual

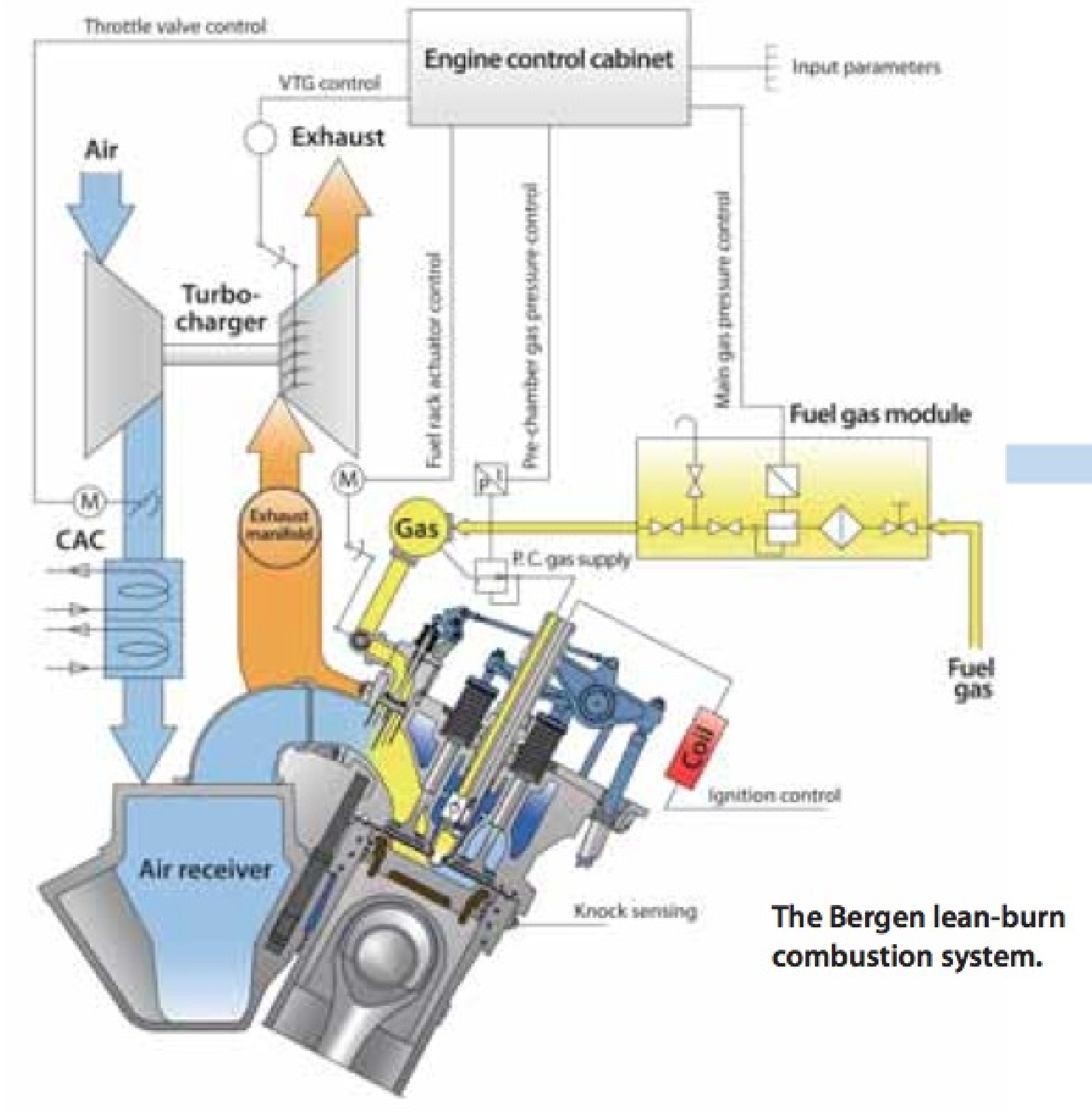


Figure 4.7: The gas supply of an Rolls-Royce single fuel engine, Rolls-Royce (2009).

fuel and single fuel engines, TGA (2011a).

LNG Infrastructure

A key issue for introduction of LNG as a bunker fuel is the availability of LNG. LNG has to be a viable alternative to conventional fuels to make sure that this type of fuel is available for ships. To operate on LNG requires a string of supply chain facilities and services in addition to the investments that are needed directly on the vessels. It is necessary for both LNG and conventional fuel to be present at or close to locations where LNG filling stations are being constructed, since LNG fuelled engines today require diesel as a pilot fuel to ingite the LNG, DMA (2011a).

Figure 4.8: Infrastructure - LNG port terminals, DMA (2011a).

The MARINTEK (2008) report shows an increasing number of LNG import terminals in Europe, and it can be concluded that LNG as an energy source is available throughout Europe and plans exist for new terminals in the Baltic area.

Degrading

Maintenance for the gas engine includes routine maintenance and overhauling. An annual maintenance interval is assumed for routine maintenance of valves, operators, heat exchangers, and pumps. The tanks, gasification equipment, and gas supply units undergo an overhaul every 5 years, TGA (2011a).

Part II

Theoretical Framework

5. Deciding on Cost-Benefit Analysis or Cost-Effectiveness Analysis

This chapter outlines the theoretical framework for the method used in Part III - Case Study and Part IV - Cost-Effectiveness Analysis.

Both cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA) are useful tools for project evaluations. These analyses can be applied before, after or during a project, and they can be of great assistance when determining whether a project is financially feasible or not, Cellini and Kee (2010) & Boardman et al. (2006).

The process in a CBA involves weighing the total expected costs against the total expected benefits of a project, while the CEA is a technique that relates the cost of a project to its benefits.

A CBA is most useful when a project is to be analyzed to decide if the total benefits of the project exceed the costs, or when alternative projects are to be analyzed to see which one achieves the greatest benefit. Costs and benefits are not always tangible or can be expressed in monetary terms. However, costs are usually easier to find and measure than benefits. Thus, the main challenge with CBA is to monetize all (or most) costs and benefits, Cellini and Kee (2010).

A CEA is most useful when the outcome is known and the objective is to determine which set of alternative projects achieves the greatest outcome, Cellini and Kee (2010). CEA compares the costs and benefits of a project to evaluate the extent to which the project can be regarded as "value for money". The aim of the analysis is to maximize the level of benefits relative to the costs. The main challenge with the CEA is that it provides no value for the output, leaving that to the subjective judgment of the analyst.

The CBA is considered the most difficult and time consuming process. The CEA is a good starting point by requiring the analyst to identify the most important outcome and relate that to the EURs spent on the project, Cellini and Kee (2010).

6. Cost-Effectiveness Analysis

Cost-effectiveness analysis seeks to identify and place EURs on the costs of a project. It then relates these costs to specific measures of project effectiveness. A project's cost-effectiveness ratio (CER) can be obtained by dividing costs by *units of effectiveness*, Cellini and Kee (2010):

$$CER = \frac{C_{Total}}{E} \tag{6.1}$$

Units of effectiveness is a measure of any quantifiable outcome central to the project's objectives. In the case study, the amount of emissions reduced (in tons) is an obvious unit of effectiveness. The CER can then be interpreted as "EURs per tons of emission reduced". The CER for a scenario can be compared to the CER for the other scenarios, to determine which scenario that costs less per unit of emission reduced.

6.1 Keys Steps in Cost-Effectiveness Analysis

Step 1: Set the Baseline for the Analysis

- Identify the problems to be addressed and the goals to be achieved;
- Specify the set of alternatives, including a "Base Case" option in which only maintenance of the existing project is carried out over the lifetime of the project; and
- Describe the alternative "With Project" options, why they have been chosen and how they are going to be implemented.

Step 2: Decide Whose Costs and Benefits Should Be Recognized

Almost every project involves a broad range of stakeholders within society, and every cost or benefit affects a particular group of people. The key issue is how to define *society*. However, it is recommended to define society by "the one that bears the costs and receive the majority of the benefits", Cellini and Kee (2010).

Step 3: Identify and Categorize Costs and Benefits

All costs and benefits cannot be known for certain. Those costs and benefits that have the most significant impact on the project need to be addressed.

Costs

All expenditures that incur during the lifetime of a project must be included in a cost-effectiveness analysis. Costs and benefits are not always tangible or can be expressed in monetary terms. However, costs are usually easier to find and measure than benefits.

Costs include the following:

- Investment costs;
- Operational costs;
- Maintenance costs; and
- Opportunity Costs.

Investment costs, or capital costs, are those which occur rarely over the life of the project. Operational costs are ongoing costs that incur once the project begins to be used. The principal costs under this category are operational and maintenance costs, Department of Transport (2010).

The benefits lost by not executing the "next best alternative" are called opportunity costs. Or in other words, the benefits you could have received by taking an alternative action.

Benefits

Benefits are those gains to investor/owner/consumer between the base case and the project options. They occur through the life of the project, and are often difficult to measure since they can be diffuse and extensive.

Step 4: Project Cost and Benefits Over the Life of the Project

After identifying costs and benefits, first the time frame of the project must be set. The lifetime must be long enough to capture most of the projects costs and benefits. Second, predictions of how the costs and benefits will change over time. Will the costs and benefits stay the same each year, or will they increase, decrease or disappear over time?

Step 5: Monetize Costs

The next step is to assign a EUR value to each cost. It is important to state the nature of the cost, how it is measured, and any assumptions made in the calculations. These assumptions have to be subjected to a sensitivity analysis, explained in Step 9.

Step 6: Quantify Benefits

The most important benefits are quantified to get the units of effectiveness. If more than one benefit is considered important, separate cost-effectiveness ratios for the additional outcomes are calculated and discussed.

Since one of the CEA's strengths is its ability to provide comparisons with other projects, the measure of effectiveness has to be a common benefit. In the case study, the units of effectiveness are the reduced emissions of SO_x and NO_x. The idea of quantifying the units of effectiveness is to count only the units of effectiveness that are added to the program: that is the effects of installing an abatement measure compared to the reference point.

Step 7: Discount Costs and Benefits to Obtain Present Values

In a cost-effectiveness analysis, since many of the costs are realized in the future, it is recommended that the present value of the costs is determined. The present value of costs is today's value of the collected costs that incur in different periods of the project lifetime:

$$PVC = I_0 + \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} \tag{6.2}$$

Where:

I_0	is the initial investment cost in year 0;
C_t	is the cost in year t;
r	is the discount rate that is assumed to be constant in the analysis time horizon;
t	is the time period when the cost incurred; and
n	is the project lifetime in years.

Step 8: Compute a Cost-Effectiveness Ratio

Here, the total cost, C_{Total}, from Formula 6.1, is substituted with the present value of the total costs PVC:

$$CER = \frac{PVC}{E} \tag{6.3}$$

An alternative is to calculate the Incremental Cost-Effective Ratio (ICER). The ICER represents the extra cost you pay for each extra unit of effectiveness gained by implementing a measure, compared to the next most effective alternative, Cellini and Kee (2010):

$$ICER = \frac{\Delta PVC}{\Delta E} \tag{6.4}$$

Step 9: Perform Sensitivity Analysis

The cost-effectiveness ratios are based on predictions of costs and benefits, and there are many factors that are subject to uncertainty. It is important to test the sensitivity of the analysis to see if the results are questionable or robust.

There are two main types of sensitivity analysis; partial and extreme case. The partial sensitivity analysis is an approach that varies one assumption at a time, holding all else constant. Uncertain parameters are varied in order to see how a change will affect the analysis. In the extreme case sensitivity analysis all the uncertain parameters are varied simultaneously.

Step 10: Make a Recommendation

The final step in a cost-effectiveness analysis is to make a recommendation, if appropriate. In cost-effectiveness analysis there is no clear decision rule when evaluating one project. The results are judged based on the analyst's subjective opinion. However, when the projects are evaluated against the same unit of effectiveness, the alternative with the lowest cost-effectiveness ratio should be recommended.

Part III

Case Study

7. Case Description

This chapter establishes the context of a hypothetical decision problem for a shipping company operating in the Baltic Sea area.

Figure 7.1: The Baltic Sea area, DNV (2010).

The shipping company operates a fleet of Ro-Ro ships. The ships are sister ships, where the oldest are built in the period 2011-2015 and the newest are built in 2016. The ships are in liner traffic, which means that they have a regular route with scheduled services in the Baltic Sea ECA, Figure 7.1. The shipping company has to make some changes to the ships, if the trade is to be continued in the area the next 20 years (2015-2035).

The alternatives for complying with the MARPOL Conventions' Regulation 13 and 14 are identified as:

- Scenario 0: Use Marine Gas Oil (MGO) to comply with the sulphur requirements, no other abatement measures installed;
- Scenario 1: Use Heavy Fuel Oil (HFO) but add scrubber and SCR to reduce SO_x and NO_x emissions, respectively;
- Scenario 2: Use Marine Gas Oil (MGO) together with an SCR; and
- Scenario 3: Use Liquefied Natural Gas (LNG).

Which strategy that will be utilized is largely dependent on investment costs, annual operational costs and the future fuel prices. The company wishes to keep its "green profile", but the ship owner wants to know which solution is the most cost-effective.

7.1 Ship Characteristics

The vessel chosen for this study is a 5,200 dwt Ro-Ro vessel. The vessel details have been found in Shipbase (2012). The service speed is 25 knots. More details are provided in Table 7.1.

Figure 7.2: Reference Ship, Shipbase (2012).

Table 7.1: Ship characteristics

Main Data		
Length (LOA)	154.26	[m]
Length (LPP)	138	[m]
Breadth	23.99	[m]
Depth	21.85	[m]
Deadweight	5,200	[ton]
Main engine	2 x 8.4	[MW]

7.2 Activity Description

In order to measure the economic and environmental performance of the fleet, a realistic operating profile representing the expected sailing pattern in the ECA is needed.

Distances and Sailing Duration

The following route is established for the fleet:

Rotterdam - Antwerp - Hamburg - Gdansk - Saint Petersburg - Rotterdam

The total distance for the roundtrip is 3,654 nm. It is estimated that the vessel has 48 roundtrips every year.

Table 7.2: Distances and Sailing Duration

From Port A to B:	**Distance [nm]**	**Duration [h]**
Rotterdam - Antwerp	144	6
Antwerp - Hamburg	426	17
Hamburg - Gdansk	870	35
Gdansk - Saint Petersburg	646	26
Saint Petersburg - Rotterdam	1,568	63
One Roundtrip	3,654	146
Roundtrips per year	48	[roundtrips/year]

Investment analyses are performed for a ship type both as new build and as retrofitted. The fuel price is given extra attention, as described in Chapter 9 - Marine Fuels. The input used for calculating the investments and annual costs are described in detail in Part IV - Cost-Effectiveness Analysis. The benefits in the cost-effectiveness analysis are emission reductions from SO_x and NO_x. The questions to be answered are: what is the cost per ton reduced pollutant, and which one of the strategies is the most cost-effective for new build and retrofit?

8. The Scenarios

This chapter presents a short description of the studied compliance strategies; Scrubber + SCR, MGO + SCR and LNG (single or dual fuel). The scenarios are based on a period of 20 years, spanning from 2015 to 2035.

In order to find which scenario is the best alternative, there will be a need for a reference point; a base case. The reference point usually consists of whatever would be done in the absence of any abatement measures being implemented or by following a ”business-as-usual” scenario. Since Scenario 0 is the only measure that does not have any abatement measures installed, thus no investment cost (see Chapter 12 - Economy), this scenario is chosen as a reference point. In other words, the calculated emissions and costs in the other scenarios are compared to Scenario 0 in the cost-effectiveness analysis in Part IV - Cost-Effectiveness Analysis.

8.1 Scenario 0

Scenario 0, or the base case, is not a ”do nothing” scenario. The scenario describes what would be the outcome if no technical abatement measures are implemented. In this case, the vessel will have to switch to low sulphur fuel in order to comply with the prevailing emission requirements, i.e. 0.1% sulphur since the hypothetical project is starting in 2015. Thus, the fuel used is MGO with a sulphur content of 0.1%.

No major modifications are required for operating on MGO. The total adaption cost is considered negligible compared to the MGO fuel costs, and not taken into account when comparing with the other scenarios. Assumptions about further maintenance and/or replacement of existing solutions, however, are included. In addition, negative incentives due to NO_x emissions are considered. For the retrofitted vessel, the amount of NO_x emitted does not exceed the Tier II limit. The new built vessel, however, will have to pay a tax for the NO_x emissions exceeding Tier III. The cost of not installing an abatement measure could turn out to be higher than expected. This is described in detail in Part IV - Cost-Effectiveness Analysis.

In Scenario 0, the Wärtsilä 6L46F is chosen as the diesel engine. The spesifications for the engine are listed in Table 8.1.

Table 8.1: Wärtsilä 6L46F spesifications, Wärtsilä (2012a)

Engine Power, ME	2 x 7,200	[kW]
Engine Speed	600	[rpm]
Number of Cylinders	6	
Spesific Fuel Oil Consumption	176	[g/kWh]
Spesific Lube Oil Consumption	0.7	[g/kWh]

8.2 Scenario 1

The machinery concept of combining exhaust gas scrubbers and selective catalytic reduction makes it possible to comply with both the low sulphur fuel requirements for 2015 and the IMO Tier III. The "end of pipe" solutions have the advantage of being able to use readily available HFO and existing engine solutions. The infrastructure, hence the availability, of HFO is good. The sulphur content of the HFO is 2.7%, which makes the fuel costs a lot smaller than for the other scenarios.

SCR and scrubber systems are available from many suppliers, they are relatively inexpensive to implement, and have a high potential for NO_x and SO_x reduction, respectively.

There could be an installation issue when combining the two technologies. Scrubbers occupy space which in some cases may lead to reduced cargo capacity. Together with an SCR this will mean even more loss of cargo space. Another drawback is the waste produced by the scrubbers; the infrastructure for scrubber waste deposition in ports is not yet in place, DMA (2011c). In addition, the technologies represent large maintenance and operating costs, mostly related to urea and NaOH, Wold (2012).

Wärtsilä is able to supply this machinery concept with both scrubber and SCR, as illustrated in Figure 8.1. The illustration is only included to show the installation principle. This is not the engine used in the case study, as seen in Table 8.2.

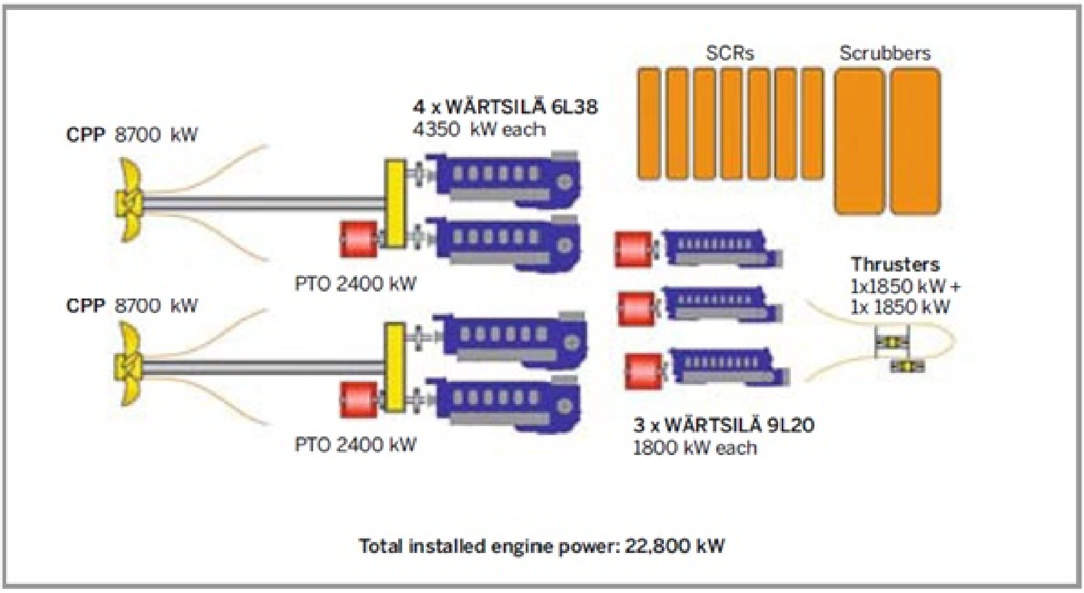


Figure 8.1: Machinery concept: W38 mechanical, Wärtsilä (2011b).

Another issue is that the scrubber cools the exhaust gas. The problem with the cooling effect is that, when an SCR unit is to be used for lowering NO_x levels, it is required that the exhaust gas is hot for it to function properly (see Chapter 4 - Abatement Measures). The SO_x must be removed from the exhaust prior to entering the SCR as the SO_x will react with ammonia and form a coating on the catalyst elements that will prevent them from working until being thoroughly cleaned. When both types of systems are installed, it may require the exhaust gas to be reheated. This is one of the reasons why the combination "scrubber + SCR" has not been widely installed yet, ABS (2010). The reduction in exhaust temperature will not permit the combination of scrubber and SCR, unless the exhaust is reheated before entering the SCR. This will also have a cost, but has not been included in the case study.

Retrofitting of scrubber will require significant modifications, including the following, Wold and Hoffmann (2011):

- Casing with existing exhaust outlets must be rebuilt;
- Continued access to engine room hatch for the aft crane must be ensured;
- Life boat may have to be moved closer to ship side;
- Placing of pumps and piping requires careful considerations;
- Existing urea tank can most likely be used as system tank if needed (e.g. NaOH); and
- The effect of scrubber installation on ship stability.

An extra investment cost of 40% compared to the new build investment costs is assumed to cover these modifications. This is explained further in Chapter 12 - Economy.

In Scenario 1, the Wärtsilä 6L46F is chosen as the diesel engine. The spesifications for the engine are listed in Table 8.2.

Table 8.2: Wärtsilä 6L46F spesifications, Wärtsilä (2012a)

Engine Power, ME	2 x 7,200	[kW]
Engine Speed	600	[rpm]
Number of Cylinders	6	
Spesific Fuel Oil Consumption	176	[g/kWh]
Spesific Lube Oil Consumption	0.7	[g/kWh]

8.3 Scenario 2

The creation of SO_2 emissions from fuel combustion is directly related to the sulphur content of fuels. Marine gas oil (MGO) is a fuel that has no problem with sulphur emissions. By changing to fuels that have limited or no sulphur content, the IMO's requirement can be met, but the engines will still need some NO_x abatement using an SCR for Tier III to be fulfilled. The fuel used is MGO with a sulphur content of 0.1%, like Scenario 0.

One of the benefits associated with operating engines on low sulphur fuels instead of HFO, are the reduced maintenance costs due to less wear on the machinery components. Adjusting the engine to MGO is a good solution for retrofitted vessels, as only small investment costs are needed, and it does not require extra volume for storage tanks. However, machinery originally designed for HFO cannot be assumed to be suitable for operation on MGO. The suitability of each component in the fuel system and the combustion system has to be checked, ABS (2010).

The operating costs will be a lot higher than for vessels running on HFO, mainly because the fuel prices for MGO are higher than for other fuels, DMA (2011c). Another issue that can arise with the usage of low sulphur fuels is that it has low lubricity because the process that reduces the sulphur also reduces the lubricating properties. This can affect pumps and other components in the fuel system, ABS (2010). Different lubrication oils will be required for safe operation of the engines.

When operating on MGO, there might be need for a fuel cooler to keep viscosity above a minimum value, ABS (2010). As mentioned in previous chapters, the efficiency of the SCR depends on a number of factors, including the exhaust gas temperature. As for Scenario 1, there might be an issue with the cooling effect when operating on MGO, and whether or not the exhaust gas has to be reheated before entering the SCR. The cooling effect of MGO has not been considered in this study.

Should ship owners want to use MGO, attention should be paid to the length of the voyage and the sailing speed. The best solution might be to burn MGO inside ECAs and to switch to HFO/LSHFO outside ECAs. For this kind of technology, a dual fuel engine has to be installed, Wärtsilä (2011b).

The chosen diesel engine for Scenario 2 is the same as for Scenario 1, Wärtsilä 6L46F. The spesifications for the engine are listed in Table 8.3.

Table 8.3: Wärtsilä 6L46F spesifications, Wärtsilä (2012a)

Engine Power, ME	2 x 7,200	[kW]
Engine Speed	600	[rpm]
Number of Cylinders	6	
Spesific Fuel Oil Consumption	176	[g/kWh]
Spesific Lube Oil Consumption	0.7	[g/kWh]

8.4 Scenario 3

Reduced emissions is the main advantage of gas engines compared to conventional diesel engines, and as an abatement measure for NO_x and SO_x it will fulfill IMO's requirements.

As mentioned in Chapter 4 - Abatement Measures, the distinction of LNG technology is usually made between dual fuel engines and single fuel engines. Scenario 3 is therefore divided into two parts:

- Dual fuel engine
- Single fuel engine

Due to its low temperature, LNG has to be stored in cryogenic tanks, which require much more space than traditional fuel oil tanks. This may reduce the cargo capacity, depending on type of vessel, type of fuel tank and location on board the vessel, DMA (2011c). Number of tanks will also vary between dual fuel and single fuel engines, where one single tank is normal for dual fuel and two tanks for single fuel engines. However, the total size will be approximately the same, TGA (2011b).

Dual Fuel Engine

The idea with dual fuel engine is to use LNG when operating in ECA and another fuel outside the ECA, which brings outstanding benefits to ship owners and operators. Since it is assumed that the vessels share of ECA operation is 100%, there will be no need for a fuel switch and the dual fuel engine will only operate on LNG.

The Wärtsilä dual fuel engine operates on the lean burn principle: the mixture of air and gas in the cylinder contains more air than is needed for complete combustion. Lean combustion reduces peak temperatures and therefore NO_x emissions. In gas mode, the engine is already compliant with IMO Tier III regulations without any secondary exhaust gas purification systems, and the technology offers zero SO_x emissions as well as smokeless operation in gas operation mode. In liquid fuel oil mode, the Wärtsilä dual fuel engines are fully compliant with the IMO Tier II exhaust emissions regulations set out in Annex VI of the MARPOL 73/78 convention, Wärtsilä (2012a).

Wärtsilä has three different dual fuel engines on the market, which are: Wärtsilä 20 DF, 34 DF and 50 DF.

Table 8.4: Wärtsilä Dual fuel engines

Engine Type	Power Range [MW]	Engine Speed [rpm]
Wärtsilä 20 DF	0.8-1.6	1,000-1,200
Wärtsilä 34 DF	2.6-7.2	720-750
Wärtsilä 50 DF	5.7-17.5	500-514

Wärtsilä 20 DF covers the lower power range in the dual fuel Wärtsilä engine family, and is suitable as a prime mover for smaller applications. Wärtsilä 34 DF fits for a various different vessel types because of the wide power range and the Wärtsilä 50 DF can be installed as a prime mover for large vessels.

In Scenario 3, the Wärtsilä 8L50DF is chosen as the dual fuel engine. The spesifications for the engine are given in Table 8.5.

Table 8.5: Wärtsilä 8L50DF spesifications, Wärtsilä (2012a)

Engine Power, ME	2 x 7,600	[kW]
Engine Speed	514	[rpm]
Number of Cylinders	8	
Spesific Fuel Oil Consumption	7,270	[kJ/kWh]
Spesific Lube Oil Consumption	0.4	[g/kWh]

Single Fuel Engine

Rolls Royce have designed Bergen lean-burn gas engines. They are designed to burn only LNG and are derived from the robust Bergen B diesel range. Compared to diesel engines that meet IMO Tier II emission levels, Bergen gas engines give an emissions reduction of 92% NO_x, close to 23% in CO_2 and virtually eliminate SO_x and particulates, and is already meeting IMO Tier III requirements that will come into force from 2016.

The two different gas engines from Rolls Royce are Bergen C26:33 and B35:40, where B35:40 have the largest engine range.

Table 8.6: Bergen Single fuel engines

Engine Type	**Power Range [kW]**	**Engine Speed [rpm]**
Bergen C26:33	1,460-2,430	1,000-1,200
Bergen B35:40	2,780-7,000	720-750

In Scenario 3, the Bergen B25:40V9PG from Rolls-Royce is chosen as the single fuel engine. The spesifications for the engine is given in Table 8.7.

Table 8.7: Rolls-Royce, Bergen B35:40V9PG, spesifications Rolls-Royce (2012)

Engine Power, ME	2 x 7,750	[kW]
Engine Speed	750	[rpm]
Number of Cylinders	9	
Spesific Fuel Oil Consumption	7,270	[kJ/kWh]
Spesific Lube Oil Consumption	0.4	[g/kWh]

The single fuel engines have slightly higher efficiency and lower emissions than comparable dual fuel engines. However, dual fuel engines offer flexibility in choosing between several types of fuel, Wold et al. (2012).

9. Marine Fuels

9.1 Fuel Standards

Marine fuels are commonly divided into two categories: residual fuel oils often referred to as heavy fuel oils (HFO), and distillates. Heavy fuel oil is the heaviest marine fuel with respect to viscosity and sulphur content. Distillate fuels can be divided into two sub-categories: marine gas oil (MGO) and marine diesel oil (MDO). When residual oil is blended with distillates, it is called intermediate fuel oil (IFO). Marine distillates are primarily used for the main engines of small vessels and auxiliary engines of larger fuels. Larger vessels usually use heavier marine fuels with occasional operation using marine diesel oil, EU (2011).

There are internationally recognized standards that define the characteristics of fuel oils and what they can contain so that they will be suitable for use on board ships. The most widely used standard is ISO 8217. The most common blends of HFO are IFO 180 and IFO 380. The number indicates the maximum viscosity in centistokes (cSt) at 50^oC. Low sulphur heavy fuel oil (LSHFO) has lower sulphur content than IFO 380 cSt, ABS (2010).

Table 9.1: Energy and sulphur contents of various fuel types, DMA (2011c)

Fuel Type	Description	Energy [MJ/kg]	Sulphur Content [%]
IFO 380 cSt	Residual fuel containing distillate fuels	40.6	3.5
LSHFO 380 cSt	Residual fuel with low sulphur content	40.6	1 or 1.5
MDO	Heavier distillate containing some residual components	42.7	0.2
MGO	Distillate only	42.7	0.1 - 0.005
LNG	Liquefied natural gas	49.2 - 49.5	0

9.2 Fuel Prices

The IFO 180 and IFO 380 heavy fuel oils, and have historically been the cheapest source of marine fuel, while MGO and MDO fuel prices have been higher than the other fuel prices. LNG prices have fluctuated less than any of the other marine fuels the last years, EMSA (2010). The costs of infrastructure and logistics have an impact on the LNG price, which means that the future fuel price level is highly uncertain, DMA (2011c).

Fuel Price Scenarios

Fuel is a major contributor to a vessel's operational costs. In order to evaluate the alternative compliance strategies; Scenario 1 (HFO + scrubber and SCR), Scenario 2 (MGO + SCR) and

Table 9.2: Fuel prices for April 2011, Wärtsilä (2012b)

Fuel Type	Fuel Price [EUR/ton]
Heavy Fuel Oil (HFO)	534
Low Sulphur Heavy Fuel Oil (LSHFO)	585
Marine Gas Oil (MGO)	748 (=1.4xHFO)
Liquefied Natural Gas (LNG)	450

Scenario 3 (LNG), it is important to have a fuel price forecast. The development of fuel prices is affected by a number of different variables (availability, infrastructure, etc.), and is therefore hard to predict.

Table 9.3: Fuel prices for April 2011, Wärtsilä (2012b)

Fuel Type	"2015 Normal" [EUR/ton]	"2015 Extreme" [EUR/ton]
Heavy Fuel Oil (HFO)	534	534
Marine Gas Oil (MGO)	961 (=1.8xHFO)	1,175(=2.2xHFO)
Liquefied Natural Gas (LNG)	748 (=1.4xHFO)	1,175(=2.2xHFO)

Wärtsilä has given an indication of what the future fuel price scenarios might look like, Table 9.3. Their approach has been used in Part IV - Cost-Effectiveness Analysis. Thus, the fuel prices for the lifetime from 2015 to 2035 are projected in two scenarios; "2015 Normal" and "2015 Extreme". The prices are assumed to be long-term and therefore constant over the 20 year long project lifetime. As seen in Table 9.3, the global demand for distillates is expected to increase, which will lead to the price of MGO increasing even more. LNG is assumed to be available at a competitive cost in the "2015 Normal" case, however in the "2015 Extreme" case, the LNG fuel price is assumed to be as high as the MGO fuel price. The price of HFO, however, is expected to stay the same in both cases.

10. Engine Operation

The first step when evaluating the economic and environmental performance of a fleet is the estimation of fuel consumed by each ship on the basis of its activities. The installed engine type on board a ship and the fuel used determines the ship's emission. Thus, information regarding the engine types used and fuel used is necessary.

10.1 Engine Description

The ship in each scenario has two main engines installed and two auxiliary engines. The sizes of the auxiliary engines are estimated to be 20% of the sizes of the main engines, Amdahl et al. (2005).

Table 10.1: The different engine types from the cost-effectiveness analysis

Engine Type	**Fuel type**	**Engine Power [kW]**
Wärtsilä 6L46F	Diesel (MGO and HFO)	7,200
Wärtsilä 8L50DF	LNG and MGO/HFO	7,600
Bergen B35:40V9PG	LNG	7,750

10.2 Operational Profile

The operational profile has three modes; "in port" (includes time spent hotelling, loading and unloading), "maneuvering" and "transit".

The distance per leg is found from the website, ports.com (2012). With a constant speed of 25.5 knots, the duration of each leg is calculated. During one year the vessel has 48 roundtrips, each roundtrip being approximately 143 hours long. This gives a total of 6,878 hours offshore every year.

Table 10.2: Duration in operational modes

Ship Operational Mode	**Duration [Hours/Year]**
Port	1,076
Maneuvering	349
Transit	6,638
Time at Sea (Maneuvering+Transit)	6,988
TOTAL	**8,064**

Where:

TOTAL	=Time in Port + Time Maneuvering + Time Transit;
Time at Sea	=(One Roundtrip × Roundtrips/Year);
Time in Port	=((24 × 7) Hours/Week × Roundtrips/Year) - Time at Sea;
Time Maneuvering	= 5%× Time at Sea; and
Time Transit	=Time at Sea - Time Maneuvering.

Machinery Load Profile

In order to calculate the fuel consumption, thus emissions, assumptions regarding the engine load are necessary for the three different ship operational modes. The assumptions are presented in Table 10.3, and are based on the Wärtsilä (2012b)-report. The engine load assumptions have considerable uncertainty and can influence the calculated emissions significantly.

Table 10.3: Machinery load profile, Scenario 1 and 2, Wärtsilä (2012b)

Ship Operational Mode	ME1	ME2	AE1	AE2
In port	-	-	40%	-
Maneuvering	50%	-	40%	-
Transit	80%	80%	-	-

For Scenario 3 the load profile is assumed different from Scenario 1 and 2.

Table 10.4: Machinery load, Scenario 3, Wärtsilä (2012b)

Ship Operational Mode	ME1	ME2	AE1	AE2
In port	-	-	40%	-
Maneuvering	50%	-	30%	-
Transit	95%	95%	40%	-

10.3 Calculating Fuel Oil Consumption

The energy consumption is found by multiplying the number of hours (in each mode), with the installed power, and the engine load:

$$EC_j\,[kWh] = \sum_{j=1}^{n} P_j\,[kW] \cdot MCR_j\,[\%] \cdot t_j\,[h] \tag{10.1}$$

Where:

j	is the index referring to the engine (ME1, ME2, AE1, etc.);
P_j	is the power of engine j [kW];
MCR_j	is the engine load for engine j [%]; and
t_j	is the number of hours engine j is in use [h].

The fuel oil consumption, FOC_j, is then calculated by multiplying the specific fuel oil consumption, $sfoc_j$, with the energy consumption. The total fuel oil consumption for each ship class in each trade is then found by summarizing the fuel oil consumption for all the engines in all the operational modes:

$$FOC_j\,[g] = \sum_{j=1}^{n} EC_j\,[kWh] \cdot sfoc_j\left[\tfrac{g}{kWh}\right] \tag{10.2}$$

The specific fuel oil consumption for the base case, Scenario 1 and Scenario 2 is assumed to be 176 [g/kWh].

Since the energy density of natural gas can vary significantly, the specific fuel consumption for natural gas is given in energy based units, [kJ/kWh], rather than mass based units, [g/kWh] TGA (2011b). Because of this, the specific LNG consumption has to be calculated beforehand:

$$sgc_j\left[\tfrac{g}{kWh}\right] = \frac{\mathrm{sec}_j\left[\frac{kJ}{kWh}\right]\cdot 1{,}000\left[\frac{g}{kg}\right]}{lcv\left[\frac{kJ}{kg}\right]} \tag{10.3}$$

Where:

sgc_j	is the specific gas consumption for engine j [g/kWh];
sec_j	is the specific energy consumption for engine j [kJ/kWh]; and
lcv	is the lower calorific value (49,165 [kJ/kWh] for LNG, TGA (2011a)) [kJ/kWh].

The specific gas consumption for Scenario 3 is calculated to be 150 [g/kWh].

Table 10.5: The specific fuel oil consumption for the different scenarios

Scenario	$sfoc_j$ **[g/kWh]**
Scenario 0	176.0
Scenario 1	176.0
Scenario 2	176.0
Scenario 3 (DF) & (SF)	150.0

10.4 Calculating Lube Oil Consumption

The energy consumption for calculating the lube oil consumption, LOC_j, is the same as for calculating the fuel oil consumption. The specific lube oil consumption, $sloc_j$ (and lube oil price), however, differs from engine to engine. Thus, the lube oil consumption has to be calculated separately:

$$LOC_j\,[g] = \sum_{j=1}^{n} EC_j\,[kWh] \cdot sloc_j\,\left[\tfrac{g}{kWh}\right] \tag{10.4}$$

Table 10.6: The specific lube oil consumption for the different scenarios

Scenario	$sloc_j$ **[g/kWh]**
Scenario 0	0.7
Scenario 1	0.7
Scenario 2	0.7
Scenario 3 (DF) & (SF)	0.4

The amount of SO_x and NO_x emitted from the lube oil is not included in the emission calculations.

11. Emissions

The aim of the study is to quantify emissions, and finding how they can be reduced in the most cost-effective way. The amount of fuel used is based on a "bottom-up" approach, using vessel movements and engine characteristics to generate an estimate of the SO_x and NO_x emissions. The focus of this study is emissions of SO_x and NO_x. However, the approach for calculating emissions can be used on other pollutants like; particulate matter (PM), carbon oxides (CO, CO_2) etc., as long as the emission factor is known.

11.1 Calculating Emissions

The amount of emissions of a certain pollutant, m_i, from a certain ship is found by summarizing the product of the engine load, MCR_j, the engine size, P_j, the ships estimated time at sea and the emission factor, $EF_{i,j}$. The basic calculation procedure is represented by Equation, 11.1.

$$m_i\,[g] = \sum_{j=1}^{n} EF_{i,j}\left[\tfrac{g}{kWh}\right] \cdot P_j\,[kW] \cdot MCR_j\,[\%] \cdot t_j\,[h] \tag{11.1}$$

Where:

i	refers to the selected pollutant;
j	is the index referring to the engine (ME1, ME2, AE1, etc.);
m_i	is the amount of emission i polluted [g]; and
$EF_{i,j}$	is the emission factor for pollutant i for engine j [g/kWh].

This approach is used for calculating SO_x emissions, and could also be used for other pollutants. The approach for calculating NO_x emissions is a little different, as the amount emitted depends on the combustion process, explained in Section 11.3 - NO_x.

11.2 SO_x

Emission Factor

Since the molar mass of SO_2 [64 g/mol] is two times the molar mass for sulphur [32 g/mol], the theoretical amount of sulphur dioxide formed is two times the amount of sulphur in the fuel, Wold (2012).

Based on the specific fuel consumption for the engine and the sulphur content in the fuel, the sulphur emission factor for each scenario is calculated:

$$EF_{SO_2}\left[\tfrac{g}{kWh}\right] = \frac{2 \cdot S\% \cdot sfc_j\left[\tfrac{g}{kWh}\right]}{100} \tag{11.2}$$

Where:

$S\%$	is the sulphur content in the fuel; and
sfc_j	is the specific fuel/gas consumption for engine j [g/kWh].

Table 11.1: SO_2 emission factor

Scenario	EF_{SO_2} **[g/kWh]**
Scenario 0	0.35
Scenario 1	9.50
Scenario 2	0.35
Scenario 3 (DF) & (SF)	-

Calculating SO_2 Emissions

Based on the operational profile, described in Chapter 10 - Engine Operation, the engine specifications and the calculated emission factors, the amount of SO_2 emitted per year is found. The actual amount of SO_2 emitted from the combustion of fossil fuels is 95% of the total SO_x, *ECSA* (2012). In this study, the emissions are derived assuming that all the sulphur present in the fuel is burnt to SO_2.

11.3 NO_x

NO_x Emission Limits

The NO_x emission limits for the ship engines in relation to their rated engine speed given in revolutions per minute. With the operational profile described in Section 10.2 - Operational Profile, and 48 roundtrips per year, the NO_x emission limits are as presented in Table 11.2. The IMO Tier III NO_x emission level corresponds to an 80% reduction from the IMO Tier I NO_x emission standard.

Table 11.2: NO_x emission limits

Scenario	**n [rpm]**	**Tier I limit [tons per year]**	**Tier II limit [tons per year]**	**Tier III limit [tons per year]**
Scenario 0 Scenario 1 Scenario 2	600	969	782	194
Scenario 3 (SF)	750	1,227	984	245
Scenario 3 (DF)	514	1,324	1,073	265

Emission Factor

The NO_x emission factor is assumed to be constant at 55 kg [NO_x/tons fuel]. This is a typical NO_x emission factor for an engine today, Wold (2012).

Emission factors are an important type of information for the estimation of emissions from ships. The emission factors do not only depend on the fuel characteristics. Generally, the NO_x emission factors for "in port" and "maneuvering" are different from the NO_x emission factor in "transit". The reason for this is that these operational modes start with a cold engine, which gives different emissions compared to the transit mode when the engine is already warm. Also, engine loads can change during maneuvering operations, and therefore give an increased variability in emissions, Entec (2002). These effects are not considered in this study. The NO_x emission factor applied in this study does not take the engine production year into account either. Thus, it is assumed that the emission factor is equal for both new built and retrofitted vessels.

Calculating NO_x Emissions

The NO_x emission is calculated according to the following formula:

$$m_{NO_x}\,[g] = 55\left[\frac{gNO_x}{kgfuel}\right]\cdot\frac{FC_j\,[g]}{1{,}000\left[\frac{g}{kg}\right]} \tag{11.3}$$

12. Economy

This chapter presents the basic formulas for calculating the economy in the case study. A detailed description of each scenario is given in Part IV - Cost-Effectiveness Analysis.

12.1 Calculating Costs

This section presents the basic formulas for calculating the economy in the case study. A detailed description of each scenario is given in the subsequent chapter.

$$C^{a}_{Total} = C^{a}_{Capital} + \sum_{i=0}^{n} C^{\mathrm{a,i}}_{Annual} \tag{12.1}$$

$$C^{a}_{Annual} = C^{a}_{Operational} + \sum_{i=0}^{n} C^{\mathrm{a,i}}_{\mathrm{Maintenance}} \tag{12.2}$$

Where:

a	is the index referring to the scenario;
i	is the index referring to the year;
n	is the expected lifetime in years;
C^{a}_{Total}	is the total costs of the project for scenario a;
$C^{a}_{Capital}$	is the capital costs for scenario a;
$C^{\mathrm{a,i}}_{\mathrm{Annual}}$	is the variable costs for scenario a in year i;
$C^{\mathrm{a,i}}_{\mathrm{Operational}}$	is the operational costs for scenario a in year i; and
$C^{\mathrm{a,i}}_{\mathrm{Maintenance}}$	is the maintenance costs for scenario a in year i.

Capital Costs

Capital costs are investment costs in year 0. Investment costs are costs that:

- Are essential for the project to proceed;
- Will be avoided if the project does not proceed;
- Will be incurred before the project commences operations; and
- Are paid for by the investors.

$$C^{a}_{Capital} = P_c + C_{Extra} \tag{12.3}$$

Where:

P_c	is the investment cost for the unit in question; and
C_{Extra}	include installation costs etc..

Operational Costs

The operational costs are estimated by year starting in the first year of operation, year 1, and extending to year 20.

$$C^{\mathrm{a,i}}_{Operational} = C^{\mathrm{a,i}}_{Fuel} + C^{\mathrm{a,i}}_{LubeOil} + T^{\mathrm{a,i}}_{Environmental} + \mathrm{C}_{Other} \tag{12.4}$$

Where:

$C^{\mathrm{a,i}}_{Fuel}$	is the fuel costs for scenario a in year i;
$C^{\mathrm{a,i}}_{LubeOil}$	is the lube oil costs for scenario a in year i;
$T^{\mathrm{a,i}}_{Environmental}$	is the environmental tax exposure for scenario a in year i;
C_{Other}	include urea costs, NaOH costs, education costs, etc.; depending on the scenario.

Fuel Costs

$$C^{\mathrm{a,i}}_{Fuel} = FOC^{\mathrm{a,i}}_{j} \cdot p^{\mathrm{a,i}}_{Fuel} \tag{12.5}$$

Where:

$FOC^{\mathrm{a,i}}_{j}$	is the fuel consumption for engine j for scenario a in year i [tons];
$p^{\mathrm{a,i}}_{Fuel}$	is the fuel price for scenario a in year i [EUR/tons].

Lube Oil Costs

$$C^{\mathrm{a,i}}_{LubeOil} = LOC^{\mathrm{a,i}}_{j} \cdot p^{\mathrm{a,i}}_{LubeOil} \tag{12.6}$$

Where:

$LOC^{\mathrm{a,i}}_{j}$	is the lube oil consumption for engine j for scenario a in year i [tons];
$p^{\mathrm{a,i}}_{LubeOil}$	is the lube oil price for scenario a in year i [EUR/tons].

Environmental Tax Exposure

NO_x emissions from ships are regulated by the IMO's Tier limits, described in Part I - Background Information. The environmental tax only applies to the amount of NO_x emitted from the vessel that exceeds the Tier limit. The tax in the trade area is assumed to be the same as the present tax in Norway; NOK 15, or approximately EUR 2 per kg NO_x.

$$C^{\text{a,i}}_{NO_x,tax} = P^{\text{a,i}}_{NO_x} \cdot m^{\text{a,i}}_{NO_x} \tag{12.7}$$

$$m^{\text{a,i}}_{NO_x} = (m_{NO_x actual} - m_{NO_x allowed})^{\text{a,i}} \tag{12.8}$$

Where:

$P^{\text{a,i}}_{NO_x}$	is the tax per kg NO_x for scenario a in year i [EUR/tons];
$m^{\text{a,i}}_{NO_x}$	is the amount of NO_x emitted in scenario a in year i [tons].

Present Value

As described in Part II - Theoretical Framework, in order to compare and sum up the costs, incurred in different years, the present value has to be calculated. The present value of costs is calculated according to the following formula:

$$PV^a = C_{Capital} + \sum_{t=0}^{n} \frac{C_{Annual}}{(1+r)^i} \tag{12.9}$$

Where:

r	is the discount rate [%].

The discount rate is assumed to be 4% throughout the lifetime of the project.

Part IV

Cost-Effectiveness Analysis

13. Costs and Emissions

13.1 Scenario 0

Emissions

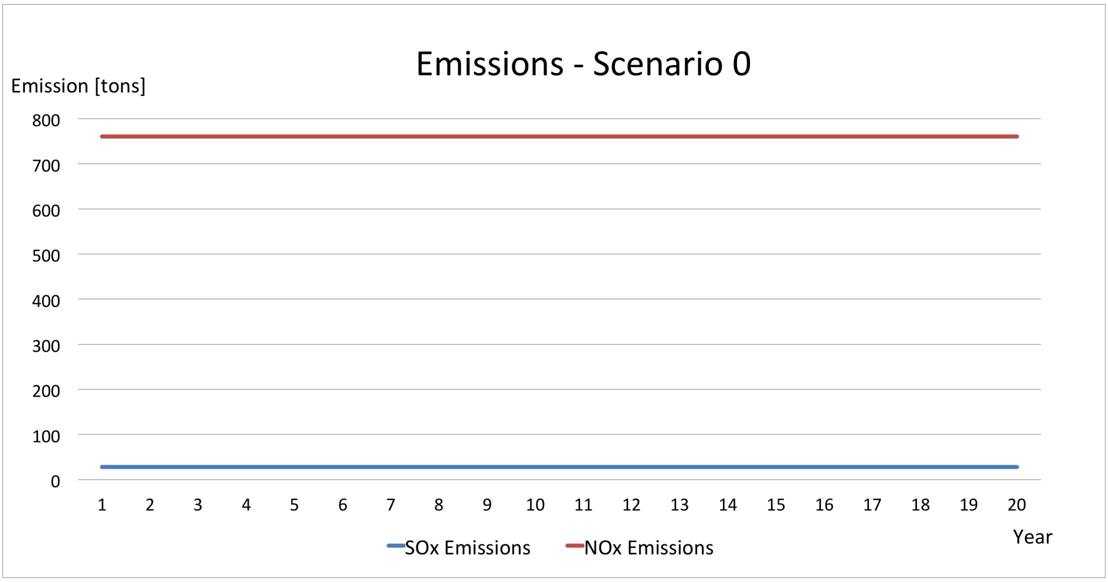


Figure 13.1: NO_x and SO_x emissons in Scenario 0

With a total energy consumption of approximately 13,800 [kWh] per year and 600 [rpm], the yearly amount of NO_x emitted is 760 [tons]. With MGO fuel and a sulphur content of 0.1%, the yearly amount of SO_x emitted is 28 [tons]. The emissions are based on the fuel oil consumption only (the lube oil consumption is not included in the emission calculations).

The total NO_x and SO_x amount emitted during the lifetime of the project is 15,208 [tons] and 553 [tons], respectively.

For the retrofitted vessel, constructed in the period 2011 to 2015, Tier II applies. For the new built vessel, built in 2016, Tier III applies.

Table 13.1: NO_x emissions for taxation

Vessel	**Tier Limit** $m_{NO_x,\text{allowed}}$	NO_x **Emitted** $m_{NO_x,\text{actual}}$	**Net** NO_x **for Taxation** m_{NO_x}
New build	197 [tons]	760 [tons]	563 [tons]
Retrofit	794 [tons]	760 [tons]	0

Formula 13.1 shows how the amount of NO_x for environmental taxation is calculated:

$$m_{NO_x}\,[kgNO_x] = \left(m_{NO_{x,\mathrm{actual}}} - m_{NO_{x,\mathrm{allowed}}}\right) \tag{13.1}$$

Costs

Capital Costs

Scenario 0, or base case, has no technical abatement measures implemented, thus no investment costs in year 0.

Table 13.2: Costs for Scenario 0

		Years (0 to n)					
		0	**1**	**2**	**...**	**5**	**n**
Capital Costs	[MEUR]	0					
Operational Costs							
-Fuel Oil Costs	[1,000EUR]		7,383	7,383	...	7,383	...
-Lube Oil Costs	[1,000EUR]		88	88	...	88	...
-NO_x Tax New Build	[1,000EUR]		1,124.4	1,124.4	...	1,124.4	...
-NO_x Tax Retrofit	[1,000EUR]		0	0	...	0	...
Maintenance Costs							
-General Maintenance Costs	[1,000EUR]		797.9	797.9	...	797.9	...
SUM (OP and M) NB	**[MEUR]**		**15.3**	**15.3**	...	**15.3**	...
SUM (OP and M) R	**[MEUR]**		**14.2**	**14.2**	...	**14.2**	...
Discount Rate	4%						
PVC New Build	**[MEUR]**	**208**					
PVC Retrofit	**[MEUR]**	**193**					

Operational Costs

The operational costs consist of fuel costs, lube oil costs and maintenance costs. The operational costs are dominated by the fuel costs. The fuel used is MGO with a sulphur content of 0.1%. The MGO price is 961.2 [EUR/ton]. The lube oil price is 1,600 [EUR/ton], Wärtsilä (2012b).

There is not an environmental taxation in the Baltic Sea at the time of writing, but a NO_x-tax has been assumed to apply in the trade area. The charges on NO_x emissions have been assumed to be the same as for the Norwegian model: 15 [NOK/kg NO_x], or approximately 2 [EUR/kg NO_x] .

As explained earlier, the charges on NO_x emissions will be different from the retrofitted ship and the new built ship as the regulations depend on year of construction. The NO_x-tax is calculated accordingly:

$$C_{NO_x,\text{tax}}\,[EUR] = m_{NO_x}\,[kgNO_x] \cdot 2 \left[\frac{EUR}{kgNO_x}\right] \tag{13.2}$$

For Scenario 0, there is a constant environmental taxation every year for the new built ship, since there are no abatement measures installed. The retrofitted ship has no environmental taxation during the whole lifetime of the project.

Maintenance Costs

General maintenance costs are 10% of the total investment cost, Amdahl et al. (2005), in this case assumed to be, 6 [MNOK].

13.2 Scenario 1

Emissions

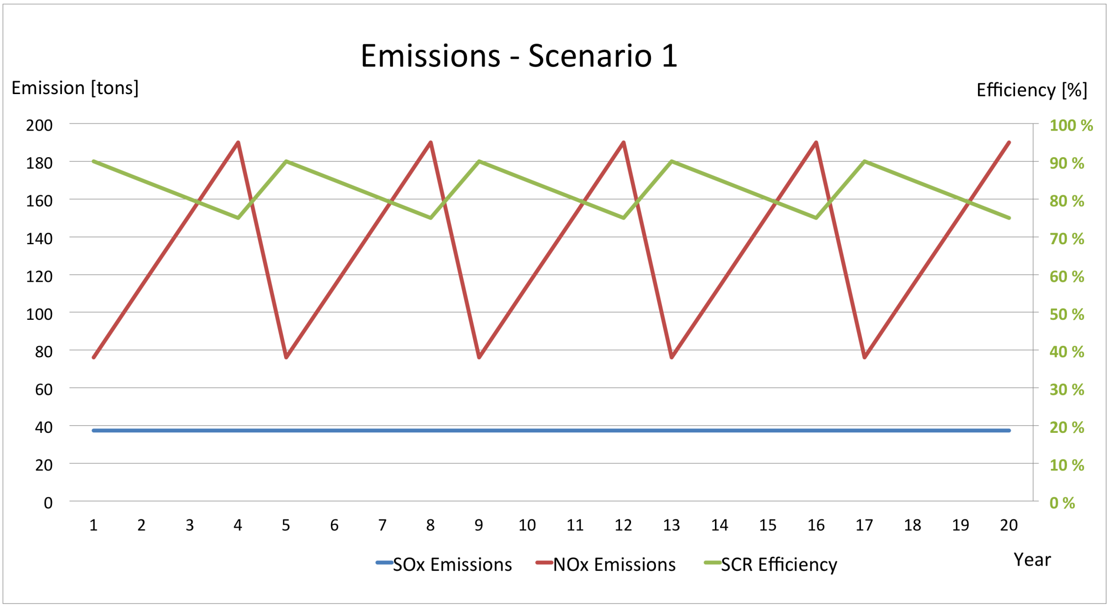


Figure 13.2: NO_x and SO_x emissons in Scenario 1

Because of the thermal and mechanical stress, the effect of the SCR is assumed to be reduced by 5% each year: starting at 90% in year 1, 85% in year 2, etc., until the catalytic elements of the SCR are replaced, and the effect is back again at 90% in year 5. 76 [tons] (90%) is the minimum amount of NO_x emitted, and 190 [tons] (75%) is the maximum amount.

The reduction effect of the scrubber is assumed to be constant at 95% every year. The total NO_x and SO_x amount emitted during the lifetime of the project is 2,661 [tons] and 747 [tons], respectively.

Costs

Capital Costs

The capital costs for installing a scrubber is estimated based on the power of the main engine, Wold (2012), accordingly:

$$C_{\text{ScrubberUnit}} = 750 + 35 \cdot P_{ME}\,[MW] = 1{,}254\,[1{,}000EUR] \tag{13.3}$$

$$C_{\text{ScrubberInstallation}} = 75 + 30 \cdot P_{ME}\,[MW] = 507\,[1{,}000EUR] \tag{13.4}$$

A price of 7 [MNOK] is estimated for an SCR for the new built vessel, Wold (2012). This cost is originally for a 10 [MW] engine, but is assumed to apply for the machinery installed in Scenario 1 as well (ME = 7,200x2 [kW]). The installation cost for an SCR unit is estimated to be 60% of the unit cost.

$$C_{\text{SCRunit}} = 931\,[1{,}000EUR] = 7\,[MNOK] \tag{13.5}$$

$$C_{\text{SCRinstallation}} = 558.6\,[1{,}000EUR] = 4.2\,[MNOK] \tag{13.6}$$

For the retrofitted vessel the cost for the scrubber unit and SCR unit are 40% higher than for the new built vessel, Wold (2012).

Operational Costs

The operational costs are dominated by the fuel costs. The fuel used is HFO with a sulphur content of 2.7%. The HFO price is 534 [EUR/ton]. The lube oil price is 1,600 [EUR/ton], Wärtsilä (2012b). Urea is normally purchased in a water solution form (around 40% concentration). Supply is not a problem and the cost is relatively low. Generally, operating costs will fluctuate with market price for urea or ammonia, Wold (2012), but in this study, the specific urea price is assumed to be constant over the lifetime of the project:

- Urea price: 0.5 EUR/liter urea (4 NOK/liter urea)
- Urea consumption: 1.5 liter urea is required to remove 1 kg NO_x

The urea costs are assumed to be constant every year, in spite of the reduced SCR effect seen in Figure 13.2. The basic formulas for calculating the urea costs are as follows:

$$C_{Urea}\,[liter] = 1.5V_{Urea}\left[\frac{liter}{kgNO_x}\right]\cdot m_{NO_x}\,[1{,}000kg]\cdot 0.5\left[\frac{EUR}{liter}\right] \tag{13.7}$$

$$m_{NO_x}\,[tons] = (m_{NO_x,S0} - m_{NO_x,S1})\,[tons] \tag{13.8}$$

Where:

$m_{NO_x,S1}$	is the amount of NO_x emitted with the SCR installed; and
m_{NO_x}	is the net reduced amount of NO_x, which gives the urea cost in Formula 13.7.

The operating costs that accompany the scrubber are estimated to be a percentage of the fuel costs, Wärtsilä (2008).

- Pumping costs: 1% (0.5-1% in average)
- NaOH costs: 2% (less than 2% in average)
- Fresh water costs are negligible

The amount of generated sludge is approximately 0.1 to 0.4 kg/MWh, EMSA (2010), however, the costs for scrubber waste disposal are neglected.

Maintenance Costs

In addition to the general maintenance costs (10% of the ship investment cost estimated to be 6 [MNOK]), maintenance costs include routine cleaning of the SCR for optimum operation, and replacement of the catalytic elements of the SCR-unit. The routine cleaning of the SCR-unit is estimated to be approximately 7,300 EUR per year based on the following assumptions, Entec (2005):

- 6 SCR cleaning events per 1,000 hours of operation
- EUR 150 per cleaning event

As explained in Section 13.2, because of the thermal and mechanical stress, the effect of the SCR is assumed to be reduced by 5% each year, starting at 90% in year 1. There will be three replacement events of the SCR catalytic elements during the lifetime of the ship (year 5, 10 and 15), as no replacement will be performed in year 20. This gives an average effect of 82.5%.

A price of 200 [1,000NOK] (3 MW) is estimated for an SCR replacement event, Wold (2012). The reactor replacement costs are calculated accordingly:

$$C_{\text{SCRreplacement}} = \frac{200{,}000[NOK]}{3{,}000[kW]} \cdot P_{ME}\,[kW] = 960\,[1{,}000NOK] = 128\,[1{,}000EUR] \tag{13.9}$$

The replacement costs makes the maintenance costs every fifth year significantly higher than compared to the other years, as seen in Table 13.3.

The scrubber effect is assumed to be constant at 95% throughout the lifetime of the project. According to the Entec (2005)-study, a lifetime of up to 12 years has been observed, and Wärtsilä delivers scrubber with a SO_x reduction of up to 97.15%.

Table 13.3: Costs for Scenario 1

		Years (0 to n)					
		0	**1**	**2**	**...**	**5**	**n**
Capital Costs New Build							
-SCR Unit Cost	[1,000EUR]	931					
-SCR Installation Cost	[1,000EUR]	558					
-Scrubber Unit Cost	[1,000EUR]	1,254					
-Scrubber Installation Cost	[1,000EUR]	507					
SUM	**[MEUR]**	**3.25**					
Capital Costs Retrofit							
-SCR Unit Cost	[1,000EUR]	1,303					
-SCR Installation Cost	[1,000EUR]	781					
-Scrubber Unit Cost	[1,000EUR]	1,756					
-Scrubber Installation Cost	[1,000EUR]	709.8					
SUM	**[MEUR]**	**4.55**					
Operational Costs							
-Fuel Oil Costs	[1,000EUR]		7,383	7,383	...	7,383	...
-Lube Oil Costs	[1,000EUR]		88	88	...	88	...
-Urea Costs	[1,000EUR]		546	546	...	546	...
-NaOH Costs	[1,000EUR]		147.7	147.7	...	147.7	...
-Pumping Costs	[MEUR]		73.8	73.8	...	73.8	...
Maintenance Costs							
-General Maintenance Costs	[1,000EUR]		797.9	797.9	...	797.9	...
-SCR Routine Cleaning Costs	[1,000EUR]		7.25	7.25	...	7.25	...
-SCR Re-Building Costs	[1,000EUR]				...	127.7	...
SUM (OP and M)	**[MEUR]**		**9.04**	**9.4**	...	**9.17**	...
Discount Rate	4%						
PVC New Build	**[MEUR]**	**126.4**					
PVC Retrofit	**[MEUR]**	**127.7**					

13.3 Scenario 2

Emissions

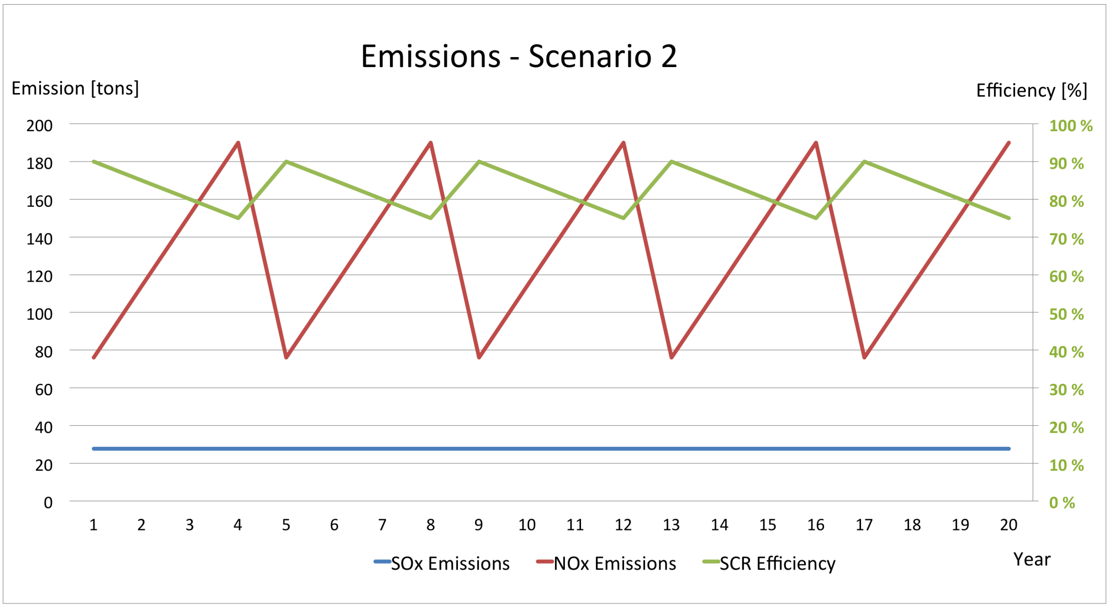


Figure 13.3: NO_x and SO_x emissons in Scenario 2

As for Scenario 1, because of the thermal and mechanical stress, the effect of the SCR is assumed to be reduced by 5% each year: starting at 90% in year 1, 85% in year 2, etc., until the catalytic elements of the SCR are replaced, and the effect is back again at 90% in year 5. 76 [tons] (90%) is the minimum amount of NO_x emitted, and 190 [tons] (75%) is the maximum amount.

The total NO_x and SO_x amount emitted during the lifetime of the project is 2,661 [tons] and 553 [tons], respectively.

Costs

Capital Costs

MGO does not require extra volume for storage tanks, and adjusting the engine to MGO causes in most cases only small investment costs, DMA (2011c). In addition, a switch to low-sulphur fuels does not require any engine modifications, Wahlström et al. (2006). The only investment costs in Scenario 2 are those for the SCR. The capital costs for the SCR technology are equal to those in Scenario 1:

$$C_{\text{SCRUnit}} = 931\,[1{,}000EUR] = 7{,}000\,[1{,}000NOK] \tag{13.10}$$

Table 13.4: Costs for Scenario 2

		Years (0 to n)					
		0	**1**	**2**	**...**	**5**	**n**
Capital Costs New Build							
-SCR Unit Cost	[1,000EUR]	931					
-SCR Installation Cost	[1,000EUR]	558					
SUM	**[MEUR]**	**1.489**					
Capital Costs Retrofit							
-SCR Unit Cost	[1,000EUR]	1,303					
-SCR Installation Cost	[1,000EUR]	781					
SUM	**[MEUR]**	**2.084**					
Operational Costs							
-Fuel Oil Costs	[1,000EUR]		13,289	13,289	...	13,289	...
-Lube Oil Costs	[1,000EUR]		88	88	...	88	...
-Urea Costs	[1,000EUR]		546	546	...	546	...
Maintenance Costs							
-General Maintenance Costs	[1,000EUR]		558.5	558.5	...	558.5	...
-SCR Routine Cleaning Costs	[1,000EUR]		7.25	7.25	...	7.25	...
-SCR Re-Building Costs	[1,000EUR]				...	127.7	...
SUM (OP and M)	**[MEUR]**		**14.48**	**14.48**	...	**14.62**	...
Discount Rate	4%						
PVC New Build	**[MEUR]**	**199**					
PVC Retrofit	**[MEUR]**	**199**					

$$C_{\text{SCRInstallation}} = 558.6\,[1{,}000EUR] = 4{,}200\,[1{,}000NOK] \tag{13.11}$$

For the retrofitted vessel the cost for the scrubber unit and SCR unit are 40% higher than for the new built vessel, Wold (2012).

Operational Costs

The operational costs will be significantly higher than for Scenario 1, mainly because of the fuel prices. The MGO fuel price is estimated to be 961.2 [EUR/tons], Chapter 9 - Marine Fuels. The lube oil price is 1,600 [EUR/ton], Wärtsilä (2012b).

As for Scenario 1, the urea costs are expected to be constant over the lifetime of the project:

- Urea price: 0.5 EUR/liter urea (4 NOK/liter urea)

- Urea consumption: 1.5 liter urea is required to remove 1 kg NO_x

The basic formulas for calculating the urea costs are as follows:

$$C_{Urea}\,[liter] = 1.5V_{Urea}\left[\frac{liter}{kgNO_x}\right] \cdot m_{NO_x}\,[1{,}000kg] \cdot 0.5\left[\frac{EUR}{liter}\right] \tag{13.12}$$

$$m_{NO_x}\,[tons] = (m_{NO_x,S0} - m_{NO_x,S1})\,[tons] \tag{13.13}$$

- Urea price: 0.5 EUR/liter urea (4 NOK/liter urea)
- Urea consumption: 1.5 liter urea is required to remove 1 kg NO_x

Maintenance Costs

Low-sulphur fuels have higher quality than regular HFO and because of that it causes less wear on the machinery and needs less lubricating oil and maintenance. This also makes the engine run smoother and reduces the risk of operating problems, EU (2011). Since the SCR also is installed in Scenario 2, the general maintenance costs are assumed to be reduced by 30% from Scenario 1. Thus, the general maintenance costs are 4.2 MNOK per year in Scenario 2. Maintenance costs also include routine cleaning of the SCR, and replacement of the catalytic elements. The routine cleaning of the SCR-unit is estimated to be approximately 7,300 EUR per year based on the following assumptions, Entec (2005):

- 6 SCR cleaning events per 1,000 hours of operation
- EUR 150 per cleaning event

The fact that the SO_x emissions are less in Scenario 2 has not been considered relevant when estimating the SCR-efficiency in Scenario 2. The effect of the SCR is assumed to be reduced by 5% each year, as for Scenario 1. This means that there will be three replacement events of the catalytic elements during the lifetime of the ship (year 5, 10 and 15) (see Equation 13.9 in Scenario 1). The replacement costs makes the maintenance costs every fifth year significantly higher than compared to the other years.

13.4 Scenario 3 - Dual Fuel Engine

Emissions

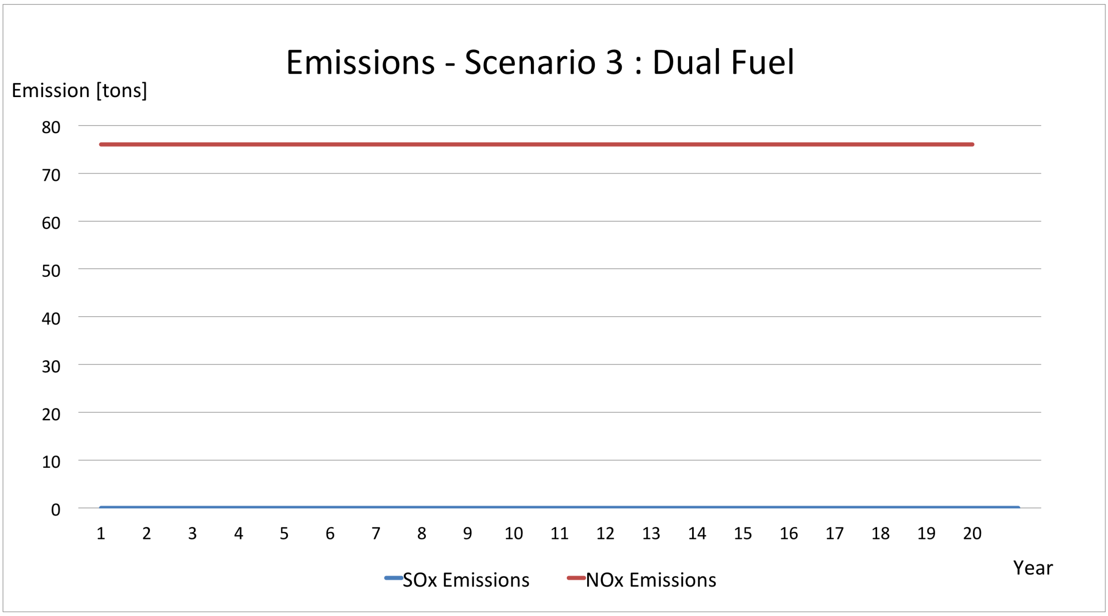


Figure 13.4: NO_x and SO_x emissons in Scenario 3 - Dual fuel engine

The reduction effect of the Dual Fuel Engine is assumed to be constant at 90% for NO_x emissions and 100% for SO_x emissions every year, Wärtsilä (2012a). The total NO_x and SO_x amount emitted during the lifetime of the project is 1,551 [tons] and 0 [tons], respectively.

Costs

Capital Costs

The capital costs for an LNG system include, Wärtsilä (2012b):

- 2 x Engine modifications
- Auxiliary systems
- Electrical & automation systems
- Engineering
- Installations
- 2 x LNGPac

The investment cost for an LNG - dual fuel engine system is very project dependant. If transportation, commissioning and yard costs are included, the capital costs are assumed to be 14,000

Table 13.5: Costs for Scenario 3 (DF)

		Years (0 to n)					
		0	**1**	**2**	**...**	**5**	**n**
Capital Costs New Build							
-LNG Investment Cost	[MEUR]	28.3					
SUM	**[MEUR]**	**28.3**					
Capital Costs Retrofit							
-LNG Investment Cost	[MEUR]	39.6					
SUM	**[MEUR]**	**39.6**					
Operational Costs							
-Fuel Oil Costs	[1,000EUR]		11,280	11,280	...	11,280	...
-Lube Oil Costs	[1,000EUR]		65.3	65.3	...	65.3	...
-Educational Costs	[1,000EUR]		53.7	53.7	...	53.7	...
Maintenance Costs							
-General Maintenance Costs	[1,000EUR]		797.9	797.9	...	797.9	...
-Overhauling	[1,000EUR]				...	68.6	...
SUM (OP and M)	**[MEUR]**		**12.20**	**12.20**	...	**12.27**	...
Discount Rate	4%						
PVC New Build	**[MEUR]**	**194**					
PVC Retrofit	**[MEUR]**	**206**					

NOK per kW, Wold et al. (2012). For the dual fuel engine the costs are:

$$C_{Investment} = 14{,}000\left[\frac{NOK}{kW}\right] \cdot (2 \times 7{,}600)\,[kW] = 212\,[MNOK] = 28.3\,[MEUR] \quad (13.14)$$

For the retrofitted vessel the cost for a dual fuel engine is 40% higher than for the new built vessel, Wold (2012).

Operational Costs

The operational costs for LNG operated vessels are fuel costs, lube oil costs and education costs. The most dominant cost is the fuel costs, with an LNG price of 747.6 [EUR/ton]. The lube oil price is 1,600 [EUR/ton], Wärtsilä (2012b).

The education costs are required when operating on LNG, and is assumed to be 50,000 USD per 6,000 operating hours, DMA (2011b). By multplying it with total operating hours for the vessel, 8,064 hours, the education costs are:

$$C_{Education} = 50\,[1,000USD] \cdot \left(\frac{8{,}064}{6{,}000}\right) = 67.2\,[1,000USD] = 53.7\,[1,000EUR] \qquad (13.15)$$

The costs for decreased cargo capacity due to the space requirements for LNG tanks are neglected.

Maintenance Costs

Maintenance costs for the LNG engine includes general maintenance costs and overhauling costs, TGA (2011b).

An annual maintenance interval is assumed for routine maintenance of valves, operators, heat exchangers, and pumps. There is no clear indication for difference in general maintenance costs compared to diesel engines, Wold et al. (2012). The general maintenance costs are therefore 10% of the ship investment cost and is estimated to be 6 [MNOK], 798 [1,000EUR]. Amdahl et al. (2005)

The tanks, gasification equipment, and gas supply units undergo an overhaul every 5 years. The costs for overhauling is estimated to be 13,000 USD per 2,300 kW, TGA (2011b). With two main engines operating, both with engine power of 7,600 [kW], the overhauling costs are:

$$C_{Overhauling} = 13,000\,[USD] \cdot \left(\frac{2\times 7{,}600}{6{,}000}\right) = 86\,[1,000USD] = 68.6\,[1,000EUR] \qquad (13.16)$$

13.5 Scenario 3 - Single Fuel Engine

Emissions

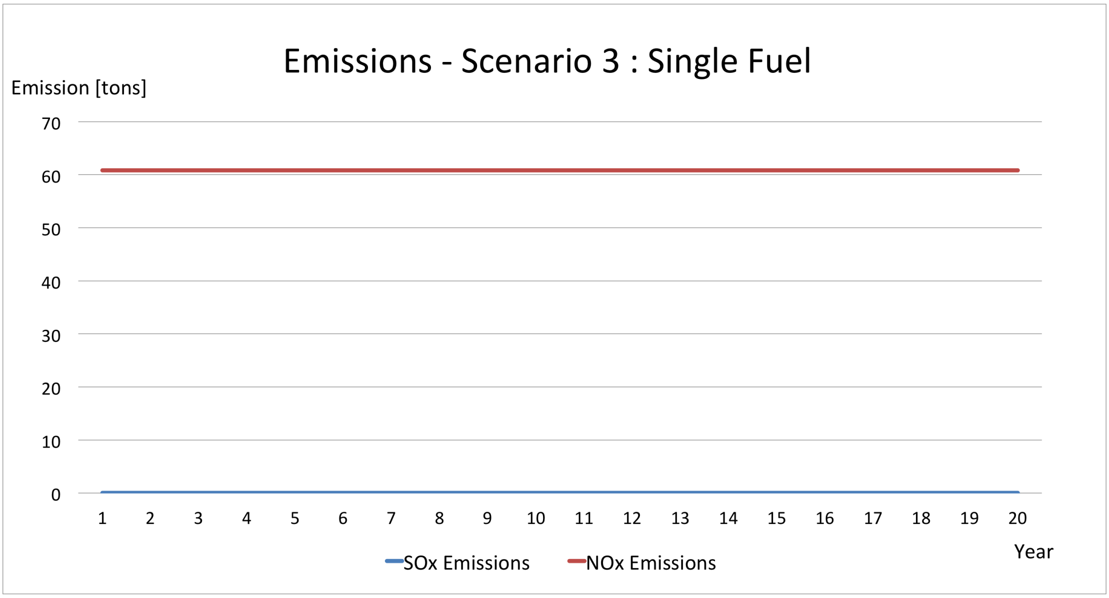


Figure 13.5: NO_x and SO_x emissons in Scenario 3 - Single fuel engine

The single fuel engine is estimated to have slightly higher efficiency and lower emissions of NO_x than comparable dual fuel engines. The reduction effect of this engine is assumed to be constant at 92% for NO_x emissions and 100% for SO_x emissions every year. The total NO_x amount emitted during the lifetime of the project is 1,217 [tons], 305 [tons] less compared to dual fuel. The total SO_x emitted is 0 [tons].

Costs

Capital Costs

The investment costs for an LNG engine system is assumed to be equal for dual fuel and single fuel engines, 14,000 NOK per kW, Wold et al. (2012).

With an engine size of 7,750 kW, the investment cost for a single fuel engine is:

$$C_{Investment} = 14,000\,[\tfrac{NOK}{kW}] \cdot (2 \times 7,750)\,[kW] = 217\,[MNOK] = 28.9\,[MEUR] \quad (13.17)$$

For the retrofitted vessel the cost for a single fuel engine 40% higher than for the new built vessel, Wold (2012).

Table 13.6: Costs for Scenario 3 (SF)

		Years (0 to n)					
		0	**1**	**2**	**...**	**5**	**n**
Capital Costs New Build							
-LNG Investment Cost	[MEUR]	28.9					
SUM	**[MEUR]**	**28.9**					
Capital Costs Retrofit							
-LNG Investment Cost	[MEUR]	40.4					
SUM	**[MEUR]**	**40.4**					
Operational Costs							
-Fuel Oil Costs	[1,000EUR]		11,502	11,502	...	11,502	...
-Lube Oil Costs	[1,000EUR]		66.6	66.6	...	66.6	...
-Educational Costs	[1,000EUR]		53.7	53.7	...	53.7	...
Maintenance Costs							
-General Maintenance Costs	[1,000EUR]		797.9	797.9	...	797.9	...
-Overhauling	[1,000EUR]				...	118.7	...
SUM (OP and M)	**[MEUR]**		**12.42**	**12.42**	...	**12.54**	...
Discount Rate	4%						
PVC New Build	**[MEUR]**	**198**					
PVC Retrofit	**[MEUR]**	**209**					

Operational Costs

The operational costs for LNG operated vessels are fuel costs, lube oil costs and educational costs. The most dominant cost is the fuel costs, with an LNG price of 747.6 [EUR/ton]. The lube oil price is 1,600 [EUR/ton], Wärtsilä (2012b).

The educational costs are similar for single fuel and dual fuel engines, and assumed to be 50,000 USD per 6,000 operating hours, DMA (2011b). The education costs are 53.7 [1,000EUR], see Equation 13.15.

Maintenance Costs

The maintenance costs for single fuel engines are equal to comparable dual fuel engines, and includes general maintenance costs and overhauling costs every 5 years, TGA (2011b).

The general maintenance costs are 10% of the ship investment cost and is estimated to be 6 [MNOK], or 798 [1,000EUR].

The tanks, gasification equipment, and gas supply units will undergo an overhaul every 5 years.

The costs for overhauling is assumed to be higher for a single fuel engine than compared to dual fuel engine, because of the complex system. The overhauling costs are therefore 21,000 USD per 2,300 kW, TGA (2011b). With two main engines operating, both with engine power of 7,750 kW, the overhauling costs are:

$$C_{Overhauling} = 13,000\,[USD] \cdot \left(\frac{2 \times 7,750}{6,000}\right) = 141.5\,[1,000USD] = 113\,[1,000EUR] \quad (13.18)$$

13.6 Summary

Table 13.7: Summary of Costs and Emissions from the Scenarios

		Scenario:				
		0	**1**	**2**	**3 DF**	**3 SF**
Costs New Build						
Investment Costs	[MEUR]	0	3	1	28	29
Operational Costs	[MEUR]	15	9	14	12	12
PVC	[MEUR]	208	126	199	194	198
Costs Retrofit						
Investment Costs	[MEUR]	0	5	2	40	40
Operational Costs	[MEUR]	14	9	14	12	12
PVC	[MEUR]	193	128	199	206	209
Emissions						
NO_x	[ton]	15,208	2,661	2,661	1,521	1,217
SO_x	[ton]	553	747	553	0	0
SO_x & NO_x	[ton]	15,761	3,408	3,214	1,521	1,217

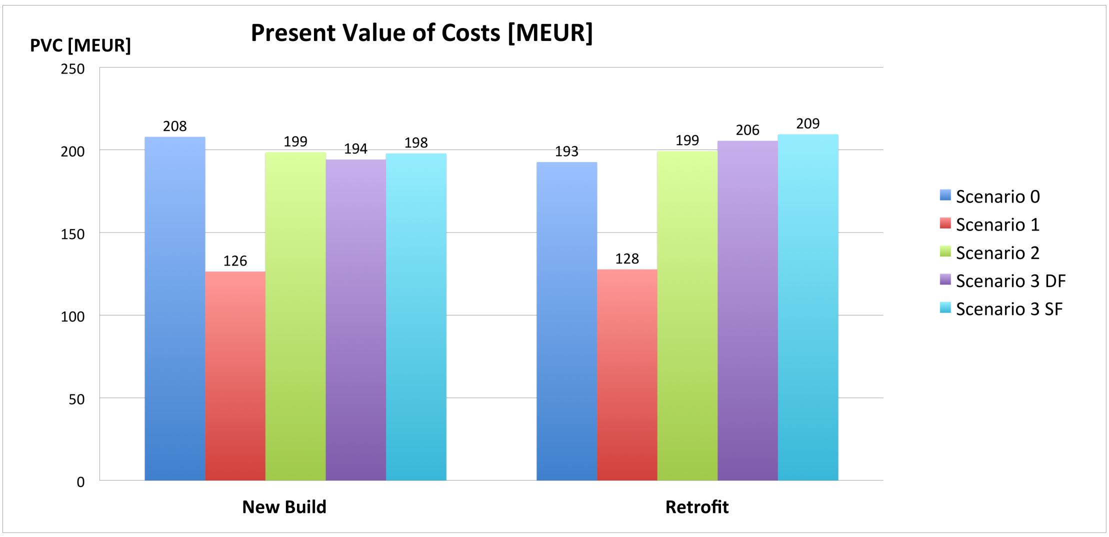


Figure 13.6: Present Value of Costs [MEUR]

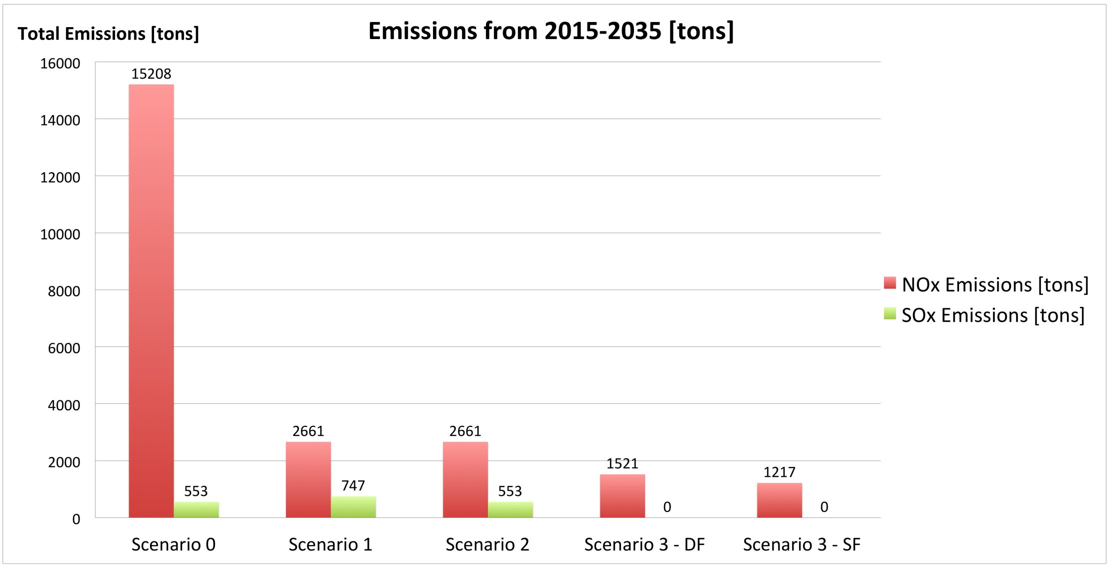


Figure 13.7: Emissions from 2015 to 2035

14. Cost-Effectiveness Analysis

As described in Part II - Theoretical Framework, the cost-effectiveness analysis (CEA) compares the costs and the units of effectiveness of a measure. The aim of the analysis is to maximize the level of benefits (emission reductions) relative to the total costs of implementing a measure.

In the case study, the scenarios are mutually exclusive in the sense that they all comply with the IMO's regulations for 2015 an onwards. When choices have to be made between different alternatives for the same condition, incremental cost-effectiveness analysis (ICEA) is a suitable technique, Phillips (2009).

The incremental cost-effectiveness ratio (ICER) is a much used measure in health economy, and represents the extra cost you pay for each extra unit of health improvement gained by using an intervention, compared to the next most effective alternative. The alternative strategies are ranked according to their effectiveness, on the basis of securing maximum effect rather than considering cost. The ICER's are calculated according to the following formula, Phillips (2009):

$$ICER = \frac{\Delta C}{\Delta E} \tag{14.1}$$

In the case study, the reference point, or base case, chosen is Scenario 0. The choice of reference point is based on the fact that the vessel has no abatement measures installed, but is still allowed to trade in the ECAs in the period from 2015-2035. Scenario 0 has the smallest/no investment cost, thus seems like the most attractive alternative for a ship owner, at least before the present value of the total costs are calculated. It is assumed that the ship owner chooses Scenario 0 unless he finds an alternative more cost-effective relative to Scenario 0.

The cost-effectiveness ratio (CER) calculated in the analysis is inspired by the incremental cost-effectiveness ratio. Instead of ranking the alternative compliance strategies, however, the scenarios are considered mutually exclusive, and therefore all scenarios are compared to the reference point, Scenario 0.

The CER for Scenario X is found from to the following formula:

$$CER\left[\frac{EUR}{tonnes}\right] = \frac{\text{Differences in PVC between Scenario 0 and Scenario X}}{\text{Differences in emissions between Scenario 0 and Scenario X}} = \frac{\Delta PVC}{\Delta E} \tag{14.2}$$

Another possibility for reference point is the scenario with the lowest cost incurred during the lifetime of the project; the lowest PVC. This alternative is evaluated in Chapter 15 - Sensitivity Analysis.

The investment cost, present value of total costs and emissions for each scenario are listed in Table 14.1.

In the following, the CER's for the different scenarios are presented. Some comments are included along the way, before a recommendation is made in the final chapter. First, a brief explanation on how to interpret the CER is presented.

Table 14.1: Reduction in present value of cost and emission relative to Scenario 0

		Scenario:				
		0 Base Case	**1**	**2**	**3 DF**	**3 SF**
PVC new build	[MEUR]	208	126	199	194	198
ΔPVC	[MEUR]		**82**	**9**	**-14**	**-10**
PVC retrofit	[MEUR]	193	128	199	206	209
ΔPVC	[MEUR]		**65**	**-7**	**-13**	**-17**
NO_x						
Emissions	[tons]	15,208	2,661	2,661	1,521	1,217
ΔE	[tons]		**12,546**	**12,546**	**13,687**	**13,991**
SO_x						
Emissions	[tons]	553	747	553	0	0
ΔE	[tons]		**-194**	**0**	**553**	**553**
SO_x & NO_x (Total)						
Emissions	[tons]	15,761	3,408	3,214	1,521	1,217
ΔE	[tons]		**12,535**	**12,546**	**14,240**	**14,544**

Interpreting the CER with Scenario 0 as Base Case

A positive CER for Scenario X means that by choosing Scenario X rather than Scenario 0, there is an improvement in the amount of emission reduced *and* a reduction in PVC. As shown in Table 14.2, a positive CER for Scenario X could also mean that Scenario X has both higher costs *and* higher emissions than Scenario 0. However, this is not the case for any of the scenarios in the case study.

A negative CER for Scenario X means that Scenario X is either a more expensive alternative, or a less effective one. This means that the CER has to be further evaluated. Since the "goal" already is accomplished in all scenarios; complying with IMO's regulations for SO_x and NO_x in the period 2015-2035, a ship owner would probably go for the scenario that has the lowest costs, period. It is not unlikely to assume that a scenario that has higher costs and lower emissions than Scenario 0 would be rejected by a ship owner.

Table 14.2: CER interpretation

+ CER	Lower costs + Lower emissions in Scenario X
	~~Higher costs + Higher emissions in Scenario X~~
− CER	Higher costs + Lower emissions in Scenario X
	Lower costs + Higher emissions in Scenario X

14.1 Cost-Effectiveness (NO_x Emissions)

The NO_x cost-effectiveness ratio for Scenario 0 is found by dividing the present value of the total costs by the total NO_x emissions for Scenario 0:

$$CER_{NO_x,S0,NB} = \frac{208{,}000[1{,}000EUR]}{15{,}208[tons]} = 13.67\left[\frac{1{,}000EUR}{tons}\right] \tag{14.3}$$

$$CER_{NO_x,S0,R} = \frac{193{,}000[1{,}000EUR]}{15{,}208[tons]} = 12.69\left[\frac{1{,}000EUR}{tons}\right] \tag{14.4}$$

For Scenario 0, the cost per ton NO_x emission for new builds and retrofits are; 13.67 [1,000EUR] and 12.69 [1,000EUR], respectively. The CER for Scenario X relative Scenario 0 is found according to the following formula:

$$CER_{NO_x} = \frac{\Delta PVC}{\Delta E_{NO_x}} = \frac{PVC_{S0} - PVC_{SX}}{E_{NO_x,S0} - E_{NO_x,SX}} \tag{14.5}$$

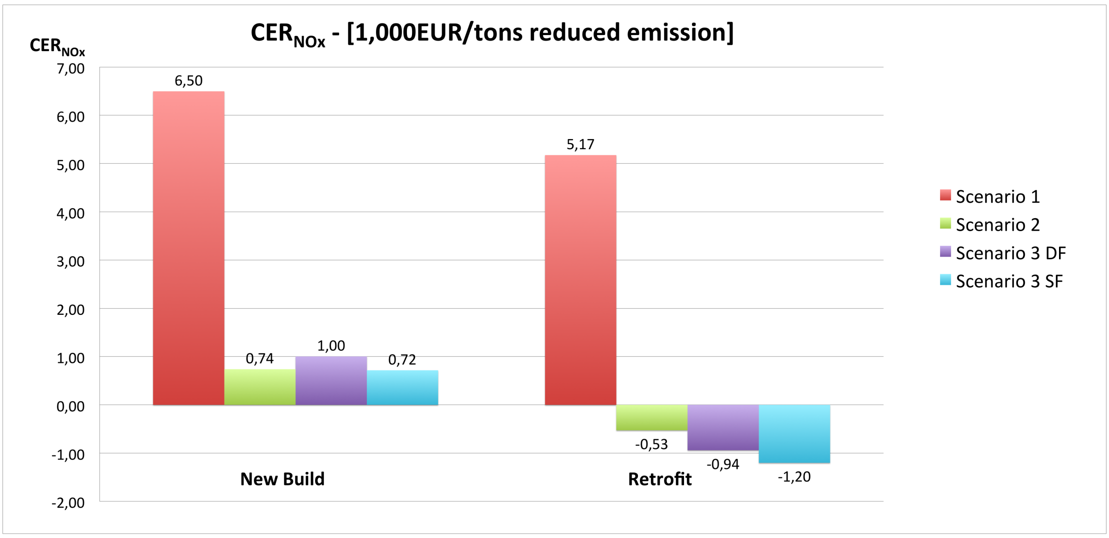


Figure 14.1: Cost-Effectiveness Ratio - NO_x for the different scenarios

Scenario 1 is the most cost-effective choice in the evaluation of CER_{NO_x} for new builds. There is an improvement in NO_x emitted *and* a reduction in costs by choosing Scenario 1 over Scenario 0:

$$CER_{NO_x,S1,NB} = \frac{208-126}{15{,}208-2{,}661} = \frac{82}{12{,}547} \approx 6.50\left[\frac{1{,}000EUR}{\text{tons reduced}}\right] \tag{14.6}$$

Table 14.3: Cost-Effectiveness Ratio - NO_x

		Scenario:			
		1	**2**	**3 DF**	**3 SF**
ΔPVC NB	[MEUR]	82	9	14	10
ΔPVC R	[MEUR]	65	-7	-13	-17
Δ E	[tons reduced emission]	12,546	12,546	13,687	13,991
$CER_{NO_x,NB}$	[1,000EUR/tons emission reduced]	6.5	0.74	1.00	0.72
$CER_{NO_x,R}$	[1,000EUR/tons emission reduced]	5.17	-0.53	-0.94	-1.20

There is also an improvement in costs by switching to single fuel LNG instead of MGO for new builds. However, the reduced amount of emission makes Scenario 3 (SF) the most "environmentally friendly" alternative, and not the most cost-effective:

$$CER_{NO_x,S3SF,NB} = \frac{208-198}{15{,}208-1{,}217} = \frac{10}{13{,}991} \approx 0.72 \left[\frac{1{,}000EUR}{\text{tons reduced}}\right] \tag{14.7}$$

For the retrofitted vessel, except from Scenario 1, all the other scenarios have negative CER_{NO_x}. Thus, Scenario 1 is the most cost-effective compliance strategy for retrofits.

When further evaluating $ICER_{NO_x}$ for the retrofits, it is observed that Scenario 3 (SF) is more expensive and more effective than Scenario 0. If the ship owner values an environmental profile, this alternative is the best choice. If the ship owner wants to minimize costs, however, Scenario 3 (SF) is rejected:

$$CER_{NO_x,S3SF,R} = \frac{193-209}{15{,}208-1{,}217} = \frac{-16}{13{,}991} \approx -1.20 \left[\frac{1{,}000EUR}{\text{tons reduced}}\right] \tag{14.8}$$

This argument also holds for Scenario 2 and Scenario 3 (DF), as both of them have lower emissions and higher costs for retrofits than Scenario 0.

14.2 Cost-Effectiveness (SO_x Emissions)

The SO_x cost-effectiveness ratio for Scenario 0 is found by dividing the present value of the total costs by the total SO_x emissions for Scenario 0:

$$CER_{SO_x,S0,NB} = \frac{208{,}000[1{,}000EUR]}{553[tons]} = 375.98 \left[\frac{1{,}000EUR}{tons}\right] \tag{14.9}$$

$$CER_{SO_x,S0,R} = \frac{193{,}000[1{,}000EUR]}{553[tons]} = 348.35 \left[\frac{1{,}000EUR}{tons}\right] \tag{14.10}$$

If the ship owner does not find a more cost-effective alternative, the cost per ton SO_x emission for new builds and retrofits are; 375.98 [1,000EUR] and 348.35 [1,000EUR], respectively.

The CER for Scenario X relative Scenario 0 is found from the following formula:

$$CER_{SO_x} = \frac{\Delta PVC}{\Delta E_{SO_x}} = \frac{PVC_{S0} - PVC_{SX}}{E_{SO_x,S0} - E_{SO_x,SX}} \tag{14.11}$$

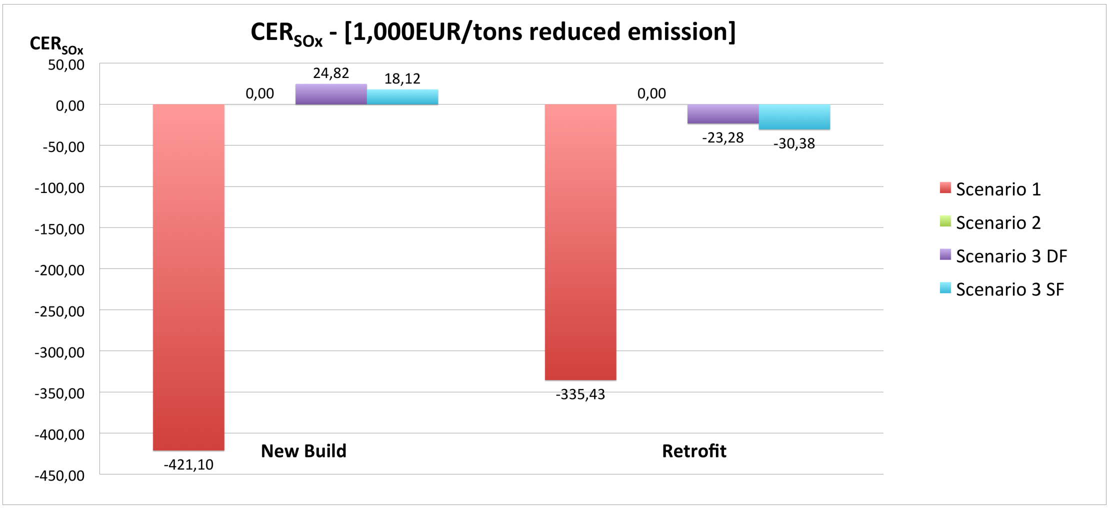


Figure 14.2: Cost-Effectiveness Ratio - SO_x for the different scenarios

Table 14.4: Cost-Effectiveness Ratio - SO_x

		Scenario:			
		1	**2**	**3 DF**	**3 SF**
ΔPVC NB	[MEUR]	82	9	14	10
ΔPVC R	[MEUR]	65	-7	-13	-17
ΔE	[tons reduced emission]	-194	0	553	553
$CER_{SO_x,NB}$	[1,000EUR/tons emission reduced]	-421.1	-	24.82	18.12
$CER_{SO_x,R}$	[1,000EUR/tons emission reduced]	335.43	-	-23.28	-30.38

When comparing the CER_{SO_x} for the scenarios, it seems like Scenario 3 (SF) is the preferred scenario for new builds. However, this result is questionable. When the ratios are further evaluated, it is observed that the cost for Scenario 3 (SF) is higher than the cost for Scenario 3 (DF):

$$CER_{SO_x,S3SF,NB} = \frac{208-198}{553-0} = \frac{10}{553} \approx 18.12 \left[\frac{1{,}000EUR}{\text{tons reduced}}\right] \tag{14.12}$$

$$CER_{SO_x,S3DF,NB} = \frac{208-194}{553-0} = \frac{14}{553} \approx 24.82 \left[\frac{1{,}000EUR}{\text{tons reduced}}\right] \tag{14.13}$$

If the focus is to minimize costs, based on the CER_{SO_x} alone, all scenarios are rejected for the retrofits.

The reason why there is no CER_{SO_x} for Scenario 2 is that the emission reduction is zero compared to Scenario 0. Both Scenario 0 and Scenario 2 have vessels running on MGO with a sulphur content of 0.1%, thus no net reduced emission.

14.3 Cost-Effectiveness (Total Emissions)

$$CER_{TOT,S0,NB} = \frac{208{,}000[1{,}000EUR]}{(15{,}208+553)[tons]} = 13.19 \left[\frac{1{,}000EUR}{\text{tons reduced}}\right] \tag{14.14}$$

$$CER_{TOT,S0,R} = \frac{193{,}000[1{,}000EUR]}{(15{,}208+553)[tons]} = 12.22 \left[\frac{1{,}000EUR}{\text{tons reduced}}\right] \tag{14.15}$$

If the ship owner does not find a more cost-effective alternative, the cost per ton emission for new builds and retrofits are; 13.19 [1,000 EUR] and 12.22 [1,000 EUR], respectively.

The CER for Scenario X relative Scenario 0 is found according to the following formula:

$$CER_{TOT} = \frac{\Delta PVC}{\Delta E_{TOT}} = \frac{PVC_{S0} - PVC_{SX}}{E_{TOT,S0} - E_{TOT,SX}} \tag{14.16}$$

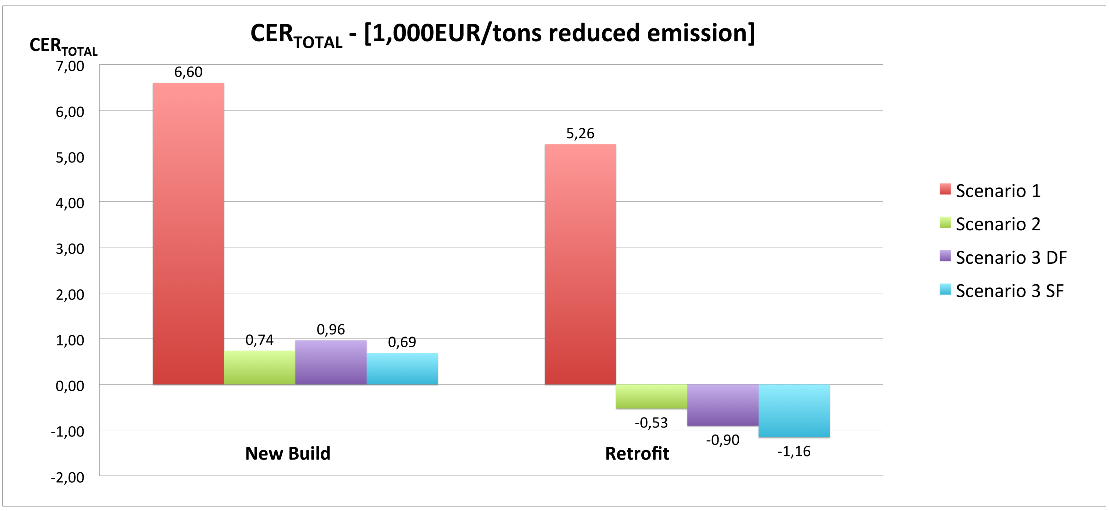


Figure 14.3: Cost-Effectiveness Ratio (Total Emissions) for the different scenarios

When summarizing both SO_x and NO_x in net reduced emissions, all CERs come out positive for the new built vessel, and all scenarios are considered cost-effective. Scenario 1 is the most cost-effective alternative for both new builds and retrofits, based on CER_{TOT}, and therefore the preferred compliance strategy.

Table 14.5: Cost-Effectiveness Ratio - Total

		Scenario:			
		1	**2**	**3 DF**	**3 SF**
ΔPVC NB	[MEUR]	82	9	14	10
ΔPVC R	[MEUR]	65	-7	-13	-17
ΔE	[tons reduced emission]	12,353	12,546	14,240	14,544
$CER_{TOT,NB}$	[1,000EUR/tons emission reduced]	6.60	0.74	0.96	0.69
$CER_{TOT,R}$	[1,000EUR/tons emission reduced]	5.26	-0.53	-0.90	-1.16

Table 14.6: Results from the cost-effectiveness analysis relative to Scenario 0

	Best Off (NB)	**Best Off (R)**	**Worst Off (NB)**	**Worst Off (R)**
CER_{NO_x}	S1	S1	S3SF	S3SF
CER_{SO_x}	S3DF	S3DF	S1	S1
CER_{TOT}	S1	S1	S3SF	S3SF

14.4 Summary

Based on CER_{NO_x}, for new builds and retrofits, the most cost-effective alternative is scrubber combined with SCR - Scenario 1. This is also the alternative with the lowest present value of total costs. However, the emissions of NO_x are in Scenario 1 the highest among all the scenarios. The most environmentally friendly compliance strategy is single fuel LNG - Scenario 3 (SF).

Relative Scenario 0, the CER_{SO_x} results are quite different from the CER_{NO_x} results. In this case, dual fuel LNG - Scenario 3 (DF), is the preferred compliance strategy, and Scenario 1 is the alternative that comes out worst when considering reduced emissions of SO_x.

When summarizing the emissions of SO_x and NO_x, with NO_x being the highest polluter, CER_{NO_x} is the ratio that dominates. For Scenario 0, the cost per ton NO_x emission for new builds and retrofits are; 13.67 [1,000 EUR] and 12.69 [1,000 EUR], respectively, while the cost per tons SO_x emission are; 375.98 [1,000 EUR] and 348.35 [1,000 EUR]. Summarizing the two pollutants and then finding the total cost-effectiveness ratio as in Section 14.3, does not give a realistic result.

To sum up, Scenario 1 provides slightly lower performance than Scenario 3 (SF) and Scenario 3 (DF), but at a significantly lower cost. Complying with IMO's Regulation 13 & 14 was a prerequisite for the scenarios to be included in the evaluation. Thus, the ship owner can decide whether he wants to minimize costs and go for Scenario 1, or maximize the emission reduction and go for Scenario 3 (SF). He can also choose to make no changes and stay with Scenario 0. Either way he has accomplished what was the original goal.

15. Sensitivity Analysis

There are considerable uncertainties related to the results in the cost-effectiveness analysis, and it should therefore be subjected to a sensitivity analysis. The ship owner has to be fully aware of the range of possible eventualities before making a decision. What would happen if the fuel price turned out to be higher than first projected, or if there were significant changes in other parameters used?

In this case, three partial sensitivity analyses are considered:

- Change of base case to identify uncertainty in the model: Scenario 1 instead of Scenario 0 (based on the lowest PVC);
- Change of the fuel price parameter: "Extreme 2015" fuel price scenario instead of "Normal 2015" fuel price scenario; and
- Change of ECA share.

15.1 Change of Base Case

Since the choice of reference point in the original cost-effectiveness analysis is based on the lowest investment cost, there are several parameters that can affect the cost-effectiveness in a long term perspective. The seemingly best do nothing-scenario could turn out to be the most expensive scenario, as there are a number of parameters that could change over the lifetime of the project.

With Scenario 1 as base case, the cost-effectiveness ratio (CER) has to be interpreted in another way than the original CER with Scenario 0 as base case.

The CER is found according to the following formula:

$$CER\left[\frac{EUR}{tons}\right] = \frac{\text{Differences in PVC between Scenario 1 and Scenario X}}{\text{Differences in emissions between Scenario 1 and Scenario X}} = \frac{\Delta PVC}{\Delta E} \tag{15.1}$$

Interpreting the CER with Scenario 1 as Base Case

In this case, since all the alternative scenarios have higher PVCs than Scenario 1, a positive CER can only mean one thing; Scenario X has higher emissions than Scenario 1. Thus, choosing a scenario with a positive CER makes no sense, and Scenario X will be rejected by the ship owner.

A negative CER means that there is an improvement in the amount of emission reduced; ΔE is positive. Thus a negative CER is preferred.

If the ship owner values an environmental profile, he will choose a scenario with a negative CER as close to zero as possible. This will be the most cost-effective scenario. If the ship owner wants to minimize the present value of the total costs, however, he will pick the scenario with a negative CER as low as possible. If the CER is zero, either the present value of the total

Table 15.1: CER interpretation

+ CER	Lower costs + Lower emissions in Scenario X
	~~Higher costs + Higher emissions in Scenario X~~
− CER	Higher costs + Lower emissions in Scenario X
	~~Lower costs + Higher emissions in Scenario X~~

costs or the emissions in Scenario X are equal to those in Scenario 0. Scenario X is then not considered cost-effective.

Cost-Effectiveness (NO_x Emissions)

The NO_x cost-effectiveness ratio for Scenario 1 is found by dividing the present value of the total costs by the total NO_x emissions for Scenario 1:

$$CER_{NO_x,S1,NB} = \frac{126{,}000[1{,}000EUR]}{2{,}661[tons]} = 47.50 \left[\frac{1{,}000EUR}{tons}\right] \tag{15.2}$$

$$CER_{NO_x,S1,R} = \frac{128{,}000[1{,}000EUR]}{2{,}661[tons]} = 47.99 \left[\frac{1{,}000EUR}{tons}\right] \tag{15.3}$$

For Scenario 1, the cost per ton NO_x emission for new builds and retrofits are; 47.5 [1,000 EUR] and 47.99 [1,000 EUR], respectively.

The CER for Scenario X relative Scenario 1 is found according to the following formula:

$$CER_{NO_x} = \frac{\Delta PVC}{\Delta E_{NO_x}} = \frac{PVC_{S1} - PVC_{SX}}{E_{NO_x,S1} - E_{NO_x,SX}} \tag{15.4}$$

Table 15.2: Cost-Effectiveness Ratio - NO_x

		Scenario:			
		0	**2**	**3 DF**	**3 SF**
PVC	[MEUR]	208	199	194	198
ΔPVC NB	[MEUR]	-82	-72	-68	-71
PVC R	[MEUR]	193	199	206	209
ΔPVC R	[MEUR]	-65	-72	-78	-82
ΔE	[tons emission reduced]	-12,546	0	1,141	1,445
$CER_{NO_x,NB}$	[1,000EUR/tons emission reduced]	6.5	-	-59.43	-49.48
$CER_{NO_x,R}$	[1,000EUR/tons emission reduced]	5.17	-	-68.21	-56.57

For new builds, Scenario 0 is rejected, since both the PVC *and* the NO_x emissions are higher than for Scenario 1. This is also the case for retrofits.

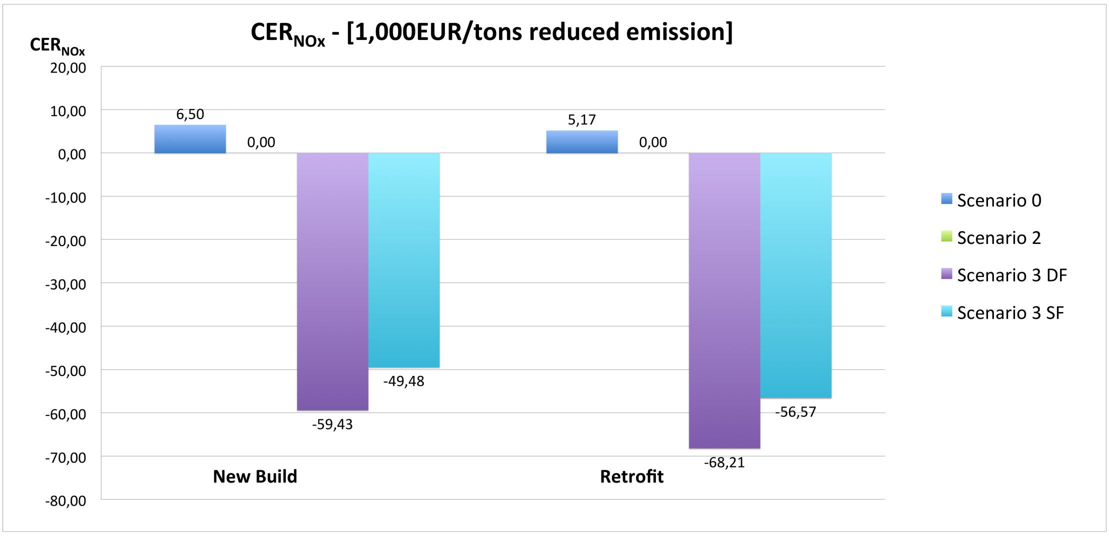


Figure 15.1: Cost-Effectiveness Ratio - NO_x for the different scenarios

Scenario 2, has no environmental improvement compared to Scenario 1, and is, with respect to the CER_{NO_x}, not considered cost-effective for neither new builds nor retrofits. Scenario 3 (SF), is regarded as the most cost-effective alternative, since the NO_x emission reduction is the highest. If the ship owners objective is to minimize the costs of the project, however, Scenario 3 (DF) is preferred for both new builds and retrofits.

Cost-Effectiveness (SO_x Emissions)

The SO_x cost-effectiveness ratio for Scenario 1 is found by dividing the present value of the total costs by the total SO_x emissions for Scenario 1:

$$CER_{SO_x,S1,NB} = \frac{126{,}000[1{,}000EUR]}{747[tons]} = 169.30\left[\frac{1{,}000EUR}{tons}\right] \tag{15.5}$$

$$CER_{SO_x,S1,R} = \frac{128{,}000[1{,}000EUR]}{747[tons]} = 171.10\left[\frac{1{,}000EUR}{tons}\right] \tag{15.6}$$

If the ship owner does not find a more cost-effective alternative, the cost per ton SO_x emission for new builds and retrofits are; 169.30 [1,000 EUR] and 171.10 [1,000 EUR], respectively.

The CER for Scenario X relative Scenario 0 is found from the following formula:

$$CER_{SO_x} = \frac{\Delta PVC}{\Delta E_{SO_x}} = \frac{PVC_{S1} - PVC_{SX}}{E_{SO_x,S1} - E_{SO_x,SX}} \tag{15.7}$$

Scenario 3 (DF) is regarded as the most cost-effective alternative for both new builds and retrofits when the CER_{SO_x} is evaluated; the emission reduction is the highest relative to the extra present value of costs.

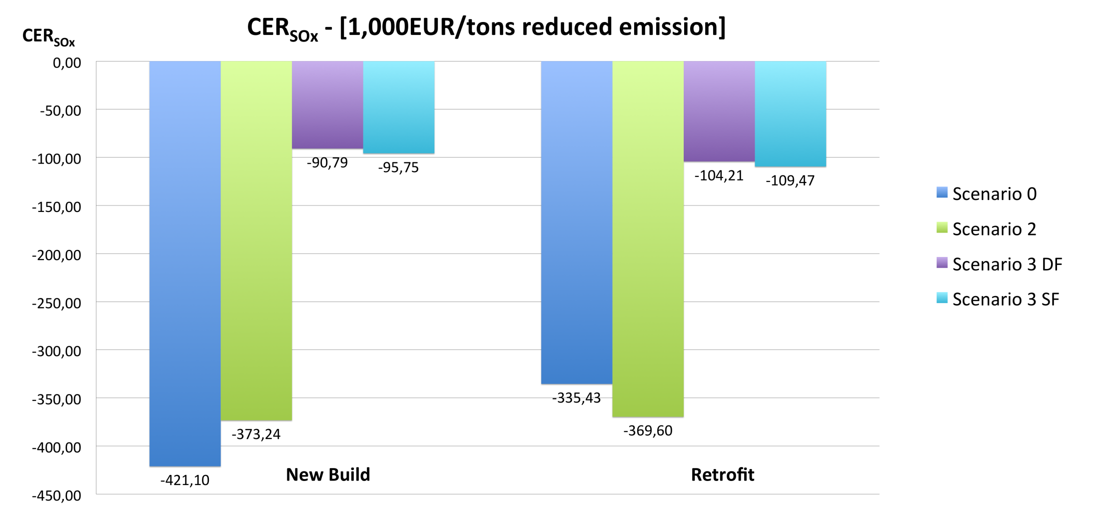


Figure 15.2: Cost-Effectiveness Ratio - SO_x for the different scenarios

Table 15.3: Cost-Effectiveness Ratio - SO_x

		Scenario:			
		0	**2**	**3 DF**	**3 SF**
PVC NB	[MEUR]	208	199	194	198
ΔPVC NB	[MEUR]	-82	-72	-68	-71
PVC R	[MEUR]	193	199	206	209
ΔPVC R	[MEUR]	-65	-72	-78	-82
ΔE	[tons emission reduced]	194	194	747	747
$CER_{SO_x,NB}$	[1,000EUR/tons emission reduced]	-421.10	-373.24	-90.79	-95.75
$CER_{SO_x,R}$	[1,000EUR/tons emission reduced]	-335.43	-369.60	-104.21	-109.47

The least cost-effective alternative for new builds is Scenario 0, with the highest costs and the lowest emission reduction. For retrofits, Scenario 2 is the least cost-effective alternative.

Cost-Effectiveness (Total Emissions)

The total cost-effectiveness ratio for Scenario 1 is found by dividing the present value of the total costs by the total NO_x and SO_x emissions for Scenario 1:

$$CER_{TOT,S1,NB} = \frac{126{,}000[1{,}000EUR]}{(2{,}661+747)[tons]} = 37.09 \left[\frac{1{,}000EUR}{\text{tons reduced}}\right] \tag{15.8}$$

$$CER_{TOT,S1,R} = \frac{128{,}000[1{,}000EUR]}{(2{,}661+747)[tons]} = 37.48 \left[\frac{1{,}000EUR}{\text{tons reduced}}\right] \tag{15.9}$$

If the ship owner does not find a more cost-effective alternative, the cost per ton emission for new builds and retrofits are; 37.09 [1,000 EUR] and 37.48 [1,000 EUR], respectively.

The CER for Scenario X relative Scenario 1 is found according to the following formula:

$$CER_{TOT} = \frac{\Delta PVC}{\Delta E_{TOT}} = \frac{PVC_{S1} - PVC_{SX}}{E_{TOT,S1} - E_{TOT,SX}} \tag{15.10}$$

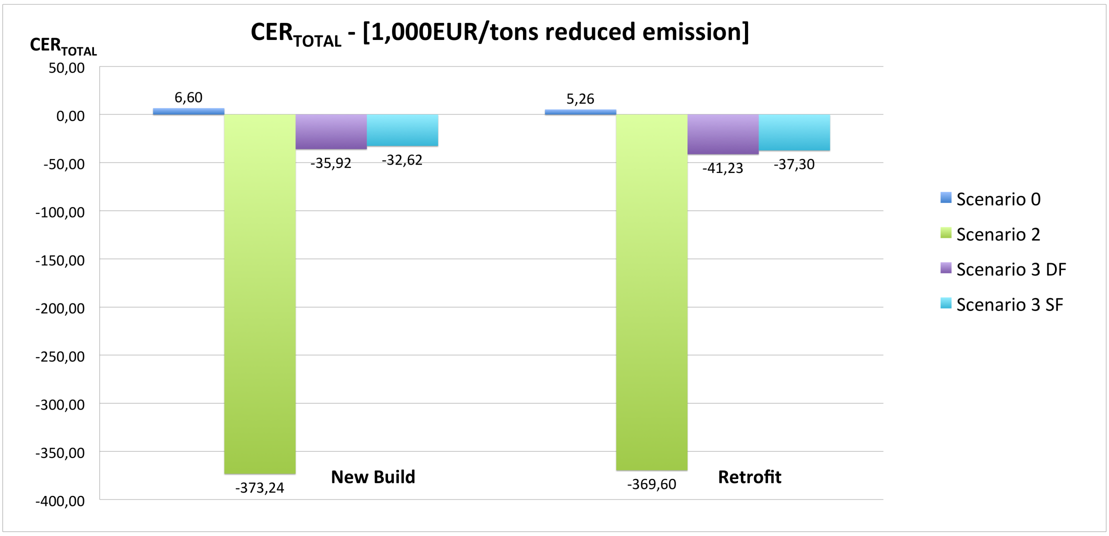


Figure 15.3: Cost-Effectiveness Ratio (Total Emissions) for the different scenarios

Table 15.4: Cost-Effectiveness Ratio - Total

		Scenario: 0	2	3 DF	3 SF
PVC NB	[MEUR]	208	199	194	198
ΔPVC NB	[MEUR]	-82	-72	-68	-71
PVC R	[MEUR]	193	199	206	209
ΔPVC R	[MEUR]	-65	-72	-76	-82
ΔE	[tons emission reduced]	-12,353	194	1,887	2,191
$CER_{TOT,NB}$	[1,000EUR/tons emission reduced]	6.60	-373.24	-35.92	-32.62
$CER_{TOT,R}$	[1,000EUR/tons emission reduced]	5.26	-369.60	-41.23	-37.30

Scenario 3 (SF) is the most cost-effective alternative when the reduced emissions of NO_x and SO_x are summarized. Scenario 0 is rejected, and Scenario 2 is considered the least cost-effective alternative. This is the case for both new builds and retrofits when evaluating the CER_{TOT}.

Figure 15.4 and 15.5 shows the net reduced emissions in tons (with Scenario 1 as base case), and the present value of total costs for all scenarios in million EURs, respectively.

Table 15.5 shows the results from the sensitivity analysis with Scenario 1 as base case. Table 15.6 shows the results from the original CEA with Scenario 0 as base case.

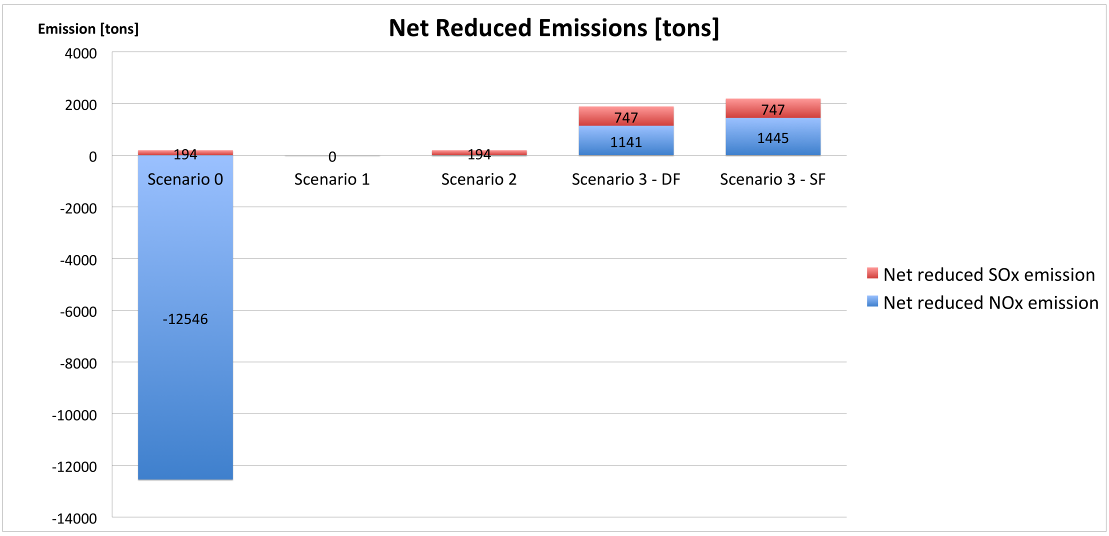


Figure 15.4: Net Reduced Emission [tons] with Scenario 1 as Base Case

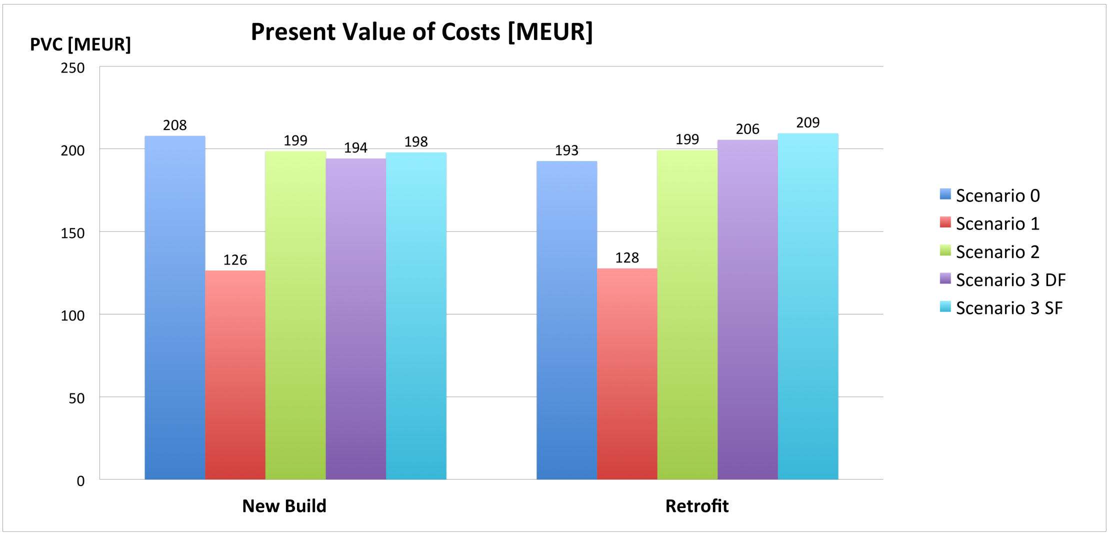


Figure 15.5: Present Value of Costs [MEUR]

Based on the cost-effectiveness ratio relative Scenario 1, the ship owner is recommended to choose Scenario 3 (SF) for both new builds and retrofits. However, Scenario 3 (SF) is considered the least cost-effective in the original cost-effectiveness analysis for both new builds and retrofits, as seen in Table 15.6. This clearly demonstrates why a sensitivity analysis is a necessity in the evaluation process of a cost-effectiveness analysis.

Figure 15.5 shows that for Scenario 0 to be cost-effective, the emission reduction for NO_x would have to be a lot higher. Scenario 0 has the lowest investment cost *and* the lowest present value of total costs for retrofits (after Scenario 1), but based on the cost-effectiveness ratios from the sensitivity analysis, the scenario is clearly not considered cost-effective in a long term perspective, and should be avoided. This is also the case for new builds. This shows that something good

Table 15.5: Results from the cost-effectiveness analysis relative to Scenario 1

	Best Off (NB)	Best Off (R)	Worst Off (NB)	Worst Off (R)
CER_{NO_x}	S3 (SF)	S3 (SF)	S0	S0
CER_{SO_x}	S3 (DF)	S3 (DF)	S0	S2
CER_{TOT}	S3 (SF)	S3 (SF)	S0	S0

Table 15.6: Results from the cost-effectiveness analysis relative to Scenario 0

	Best Off (NB)	Best Off (R)	Worst Off (NB)	Worst Off (R)
CER_{NO_x}	S1	S1	S3 (SF)	S3 (SF)
CER_{SO_x}	S3 (DF)	S3 (DF)	S1	S1
CER_{TOT}	S1	S1	S3 (SF)	S3 (SF)

came out of the sensitivity analysis. If the ship owner is about to continue the trade with no abatement measures installed, after the sensitivity analysis, he will probably reconsider.

Since the CER originally is a much used method in health economy, the value of a life is regarded as more important than the costs. Thus, the CER value, in this case study, has an environmentally friendly approach. A ship owner will most likely not have the same focus as a doctor; saving one more life cannot be compared to reducing one more ton of emission. As earlier mentioned, since all the scenarios comply with IMO's regulations for SO_x and NO_x in the period 2015-2035, a ship owner will probably choose the scenario that has the lowest present value of costs, not the lowest emissions. This is why the CER method is not sufficient alone as an evaluation method. The ship owner has to look into the costs of each scenario if he wants to spend as little money as possible on emission reductions.

15.2 Change of Fuel Price

With the fuel costs being one of the largest expenditures for a ship owner, the fuel prices are of high interest. One thing known for certain is that the fuel prices will fluctuate throughout the 20 year long lifetime of the project. How much they will differ from year to year depends on many variables and is therefore hard to predict.

Two fuel price scenarios are established: the "Normal 2015" fuel price scenario and the "Extreme 2015" fuel price scenario.

Before calculating the present value of total costs, the following assumptions are made:

- Both scenarios for each fuel type begins in 2015 and lasts throughout the project lifetime;
- All other parameters are assumed to be fixed for both fuel scenarios, including the emissions of SO_x and NO_x; and
- As described in Chapter 9 - Marine Fuels, the future MGO and LNG prices are assumed to be linked to the HFO price.

The results are subject to uncertainty, and are calculated only to demonstrate how much the fuel prices can affect the total costs of a project.

"Normal 2015" Fuel Price Scenario

In the "Normal 2015" fuel price scenario, the costs for the different fuels are as follows:

$$HFO = 534 \left[\frac{EUR}{tons}\right] \tag{15.11}$$

$$MGO = 1.8 \cdot HFO = 1.8 \cdot 534 \left[\frac{EUR}{tons}\right] = 961.2 \left[\frac{EUR}{tons}\right] \tag{15.12}$$

$$LNG = 1.4 \cdot HFO = 1.4 \cdot 534 \left[\frac{EUR}{tons}\right] = 747.6 \left[\frac{EUR}{tons}\right] \tag{15.13}$$

The fuel consumption and sulphur content for the Scenarios are listed in Table 15.7.

Table 15.7: Fuel consumption and costs for the scenarios with "Normal 2015" fuel price scenario

Scenario	Fuel Type	% Sulphur	Fuel Consumption [tons]	Fuel Costs [MEUR]
Scenario 0	MGO	0.1	13,825	13.29
Scenario 1	HFO	2.7	13,825	7.38
Scenario 2	MGO	0.1	13,825	13.29
Scenario 3 DF	LNG	0	15,088	11.28
Scenario 3 SF	LNG	0	15,386	11.50

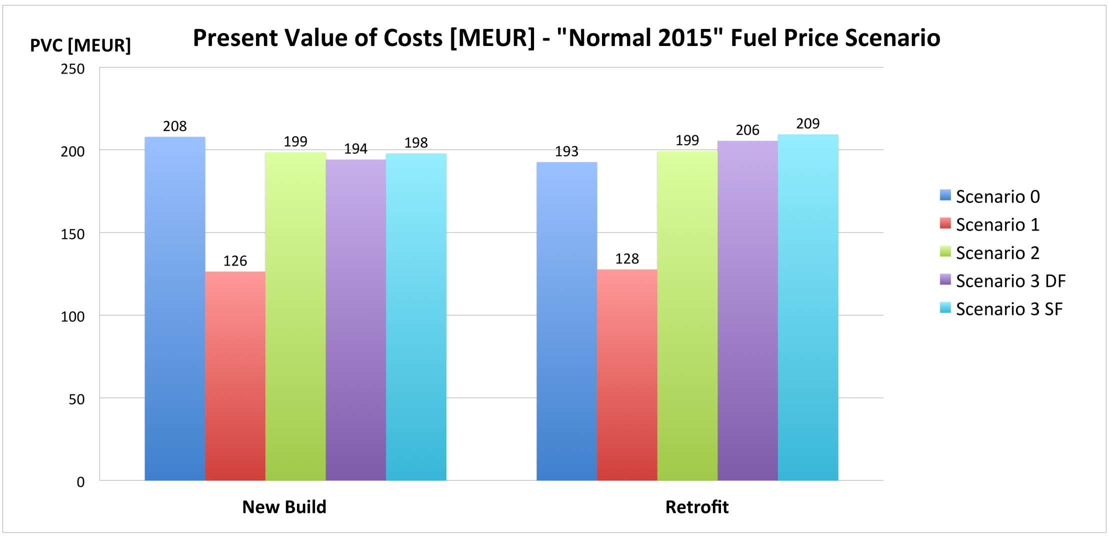


Figure 15.6: Present Value of Costs [MEUR] with "Normal 2015" fuel price scenario

For new builds, it is not surprising that the alternatives having engines operating on MGO, Scenario 0 and Scenario 2, are the ones that have the highest present value of the total costs.

For retrofits, the scenarios with engines running on LNG are the most expensive. This is partly because of the high fuel price, but also because of the fact that the investment costs for retrofitting a ship for LNG operation are high.

Based on the present value of total costs alone, the ship owner will prefer Scenario 1 as compliance strategy. The capital costs of implementing scrubber and SCR are low both for new builds and retrofits, and with the low HFO-price, the operational costs are kept low during the entire project lifetime.

”Extreme 2015” Fuel Price Scenario

In the ”Extreme 2015” fuel price scenario, the costs for the different fuels are as follows:

$$HFO = 534 \left[\frac{EUR}{tons}\right] \tag{15.14}$$

$$MGO = 2.2 \cdot HFO = 2.2 \cdot 534 \left[\frac{EUR}{tons}\right] = 2,114.64 \left[\frac{EUR}{tons}\right] \tag{15.15}$$

$$LNG = 2.2 \cdot HFO = 2.2 \cdot 534 \left[\frac{EUR}{tons}\right] = 2,114.64 \left[\frac{EUR}{tons}\right] \tag{15.16}$$

Table 15.8: Fuel consumption and sosts for the scenarios with ”Extreme 2015” fuel price scenario

Scenario	Fuel Type	% Sulphur	Fuel Consumption [tons]	Fuel Costs [MEUR]
Scenario 0	MGO	0.1	13,825	16.24
Scenario 1	HFO	2.7	13,825	7.38
Scenario 2	MGO	0.1	13,825	16.24
Scenario 3 DF	LNG	0	15,088	17.73
Scenario 3 SF	LNG	0	15,386	18.08

In the ”Extreme 2015” fuel price scenario, the present value of total costs in Scenario 1 is the same as in the ”Normal 2015” fuel price scenario; Scenario 1 is preferred for both new builds and retrofits.

Since the LNG-price is considerably higher compared to the ”Normal 2015” LNG-price, suddenly the scenarios with MGO seem more attractive than before. Based on the present value of total costs alone the ship owner would prefer Scenario 1 as compliance strategy.

Summary

Based on the two fuel price scenarios, the safest option for both new builds and retrofits is Scenario 1. For retrofits, the most expensive alternative is Scenario 3 (SF) in both fuel price scenarios.

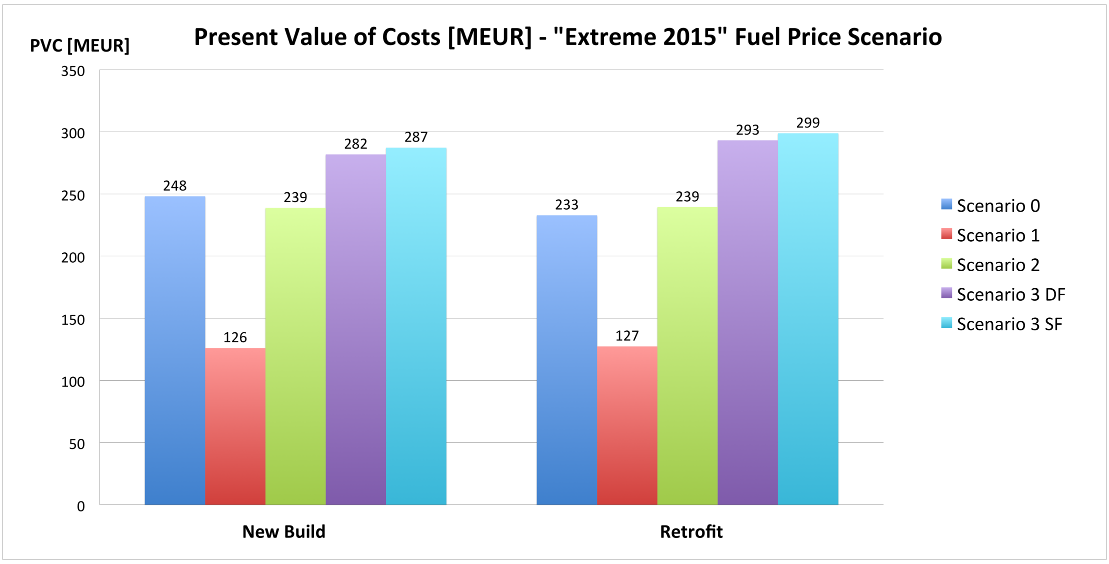


Figure 15.7: Present Value of Costs [MEUR] with "Extreme 2015" fuel price scenario

15.3 Change of ECA Share

The share of ECA operation will have an affect on the costs and emissions for the different scenarios. The reason for this affect is when the vessel is operating outside the ECA there is a possibility for fuel switch. The different fuel switch are listet in Table 15.9.

Table 15.9: Fuel type in and outside ECA

	Fuel Type Inside ECA	Fuel Type Outside ECA
Scenario 0	MGO	LSHFO
Scenario 1	HFO	HFO
Scenario 2	MGO	LSHFO
Scenario 3 DF	LNG	LSHFO
Scenario 3 SF	LNG	LNG

For 100% share of ECA operation, the limit value of 0.1% by weight in the marine fuel is applicable for SO_x after 1^{st} of January 2015. For NO_x emission Tier III in the MARPOL convention need to be fulfilled. When operating outside ECA there are other rules to conduct.

According to IMO's regulations, the limit value for sulpur when operating outside ECA is:

- 4.50% prior to 1^{st} of January 2012
- 3.50% on and after 1^{st} of January 2012
- 0.50% on and after 1^{st} of January 2020

The fuel type LSHFO with 1% sulphur content is considered when sailing outside ECA. It doesn't full the demand with a 0.5% limit value, but the most important aspect is to see how the SO_x emission vary with different share of ECA operation.

When it comes to NO_x emission Tier II for retrofitted vessels and Tier III for new builds are no longer applicable when operating outside ECA, Tier II limits are global, but since none of the scenarios exceed the NO_x limits, there will be no taxation when sailing outside ECA. The taxation inside ECAs will vary with share of ECA operation:

$$C_{NO_x,tax,\%ECA}\,[EUR] = \left(m_{NO_x}\,[kgNO_x] \cdot 2\left[\frac{EUR}{kgNO_x}\right]\right) \times \%OperationECA \tag{15.17}$$

In order to see how much the share of ECA operation can affect the present value of the total costs and the emissions, two scenarios are established: 80% ECA operation and 50% operation.

Present Value of Costs

The major contributor to the PVC change is the fuel costs. The fuel costs, with respect to share of ECA operation, is calculated by:

$$C^{\mathrm{a}}_{Fuel} = \left(FOC^{\mathrm{a}}_j \cdot p^{\mathrm{a}}_{Fuel,j}\right) \times \%ECA + \left(FOC^{\mathrm{a}}_k \cdot p^{\mathrm{a}}_{Fuel,k}\right) \times (1 - \%ECA) \tag{15.18}$$

FOC^{a}_j	is the fuel consumption for engine j for scenario a inside ECA [tons];
$p^{\mathrm{a}}_{Fuel,j}$	is the fuel price for scenario a inside ECA [EUR/tons];
FOC^{a}_k	is the fuel consumption for engine k for scenario a outside ECA [tons];
$p^{\mathrm{a}}_{Fuel,k}$	is the fuel price for scenario a outside ECA [EUR/tons];
$\%ECA$	share of operation in ECA; and
$(1 - \%ECA)$	share of operation outside ECA.

For Scenario 1 and Scenario 3 (SF) the fuel costs will stay constant, since there are no fuel switch outside ECA. The fuel costs for the other scenarios will change when the share of ECA operation is reduced (see Figure 15.8).

Since the case study considers 100% ECA operation, the dual fuel engine does not utilize its full potential. When operating outside ECA, the vessel will change to LSHFO instead of LNG. Since the fuel price for LSHFO is 585 [EUR/tons] and LNG 747.7 [EUR/tons], the fuel costs will be cheaper when the share of ECA operation is reduced. The same applies for Scenario 0 and Scenario 2 with an MGO price at 961.2 [EUR/tons].

Since the fuel costs decreases with reduced share of ECA operation, the present value of costs also gets lower (see Figure 15.9).

The present value of costs will stay constant for Scenario 1 and Scenario 3 (SF), since there are no fuel costs difference compared to 100% ECA operation. For Scenario 0, the NO_x tax is also considered (see Equation 15.17).

Emissions

With reduced share of ECA operation, the emissions of NO_x and SO_x will be affected. The NO_x and SO_x emissions can be found by using the formula:

$$m_i\,[g] = (m_{i,j} \times \%ECA) + (m_{i,k} \times (1 - \%ECA)) \tag{15.19}$$

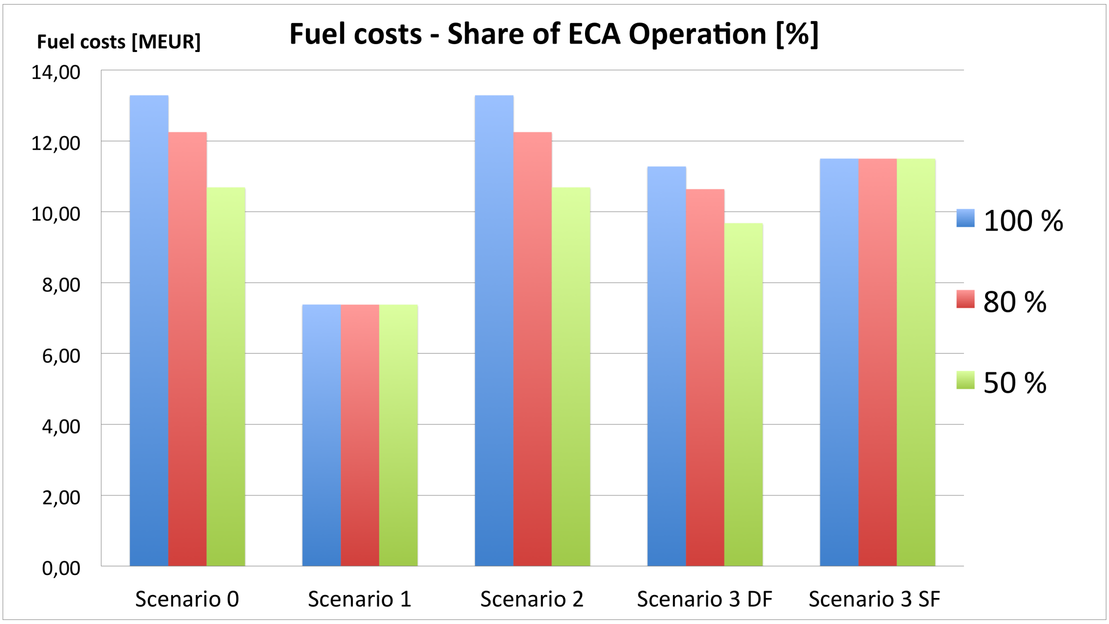


Figure 15.8: Fuel costs variation with different shares of ECA

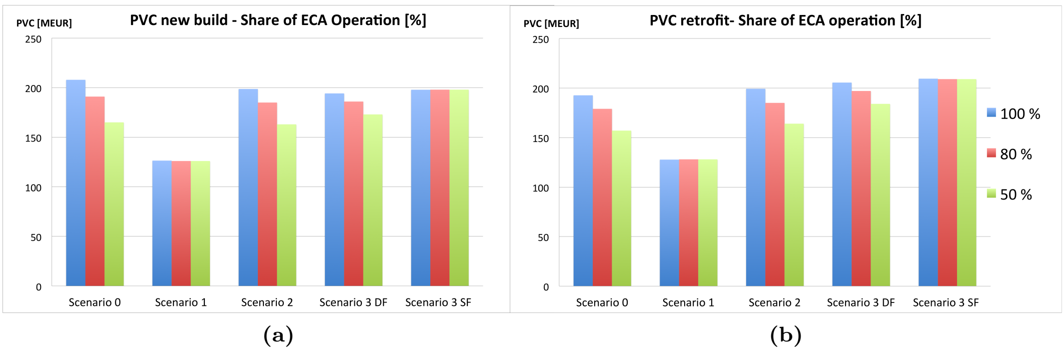


Figure 15.9: Present value of costs (PVC) in different shares of ECA (a) new build (b) retrofit

where:

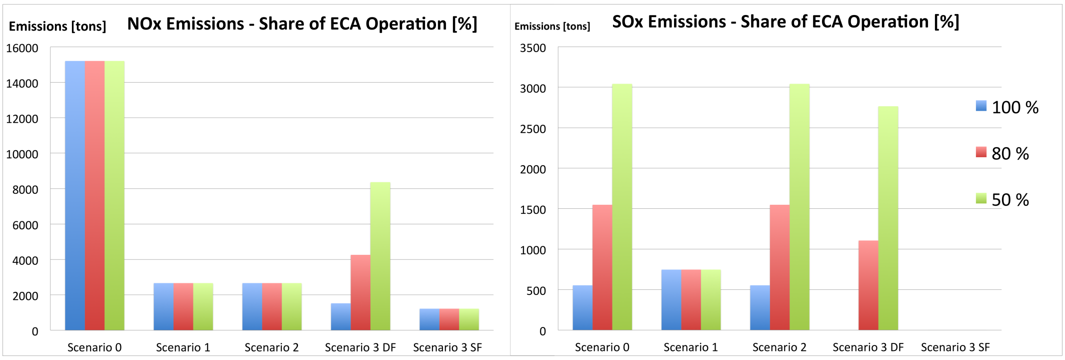
i	refers to the selected pollutant;
$m_{i,j}$	is the amount emitted NO_x inside ECA. For instant with LNG; and
$m_{i,k}$	is the amount emitted NO_x outside ECA. For instant with LSHFO.

NO_x emission will stay constant for all the scenarios except from Scenario 3 (DF).

The amount emitted NO_x for LSHFO is the same as for MGO and HFO, which is 15,208 [tons] for Scenario 0 and 2,661 [tons] for Scenario 2. The NO_x emission for Scenario 3 (DF) is increased by 2,737 [tons] from 100% operation to 50% ECA operation, since it uses diesel oil 50% of the time.

SO_x emissions vary significantly more than the NO_x emissions when the share of ECA operation is changed, because of the sulphur content in the fuel. When the sulphur content increases to

1% for LSHFO, compared to 0.1% for MGO, the emission also increases. The SO_x emissions increase with the same amount for Scenario 0 and Scenario 2 from 100 % operation to 50% operation with 2,489 tons. The SO_x emissions go from 0 to 2,765 tons with 50% decrease in ECA operation for Scenario 3 (DF).



(a) **(b)**

Figure 15.10: Emissions in different shares of ECA (a) NO_x emission (b) SO_x emission

Summary

Changing the share of ECA operation will have an affect on both present value of costs and emissions. It will be up to the shipowner to decide what the objective of the trade is, with the abatement measure, explained in Chapter 4, installed on the vessel. If the objective is to save money, decrease in the ECA share will be profitable. However, if the goal is to reduce emissions, an increase in the ECA share is desirable.

16. Conclusion

The results from this study show that scrubber in combination with SCR from a ship owners point of view is a good compliance strategy for IMO's requirements. It has the lowest fuel costs and the lowest present value of total costs among the scenarios outlined. Both for new builds and retrofits, scrubber combined with SCR is a favored solution.

Based on the cost-effectiveness analysis, having engines running on MGO is not considered cost-effective. Even though investment costs are low, changing to lighter fuels will increase fuel costs drastically.

LNG is the most environmentally friendly alternative with almost no emissions of SO_x and NO_x. In spite of the high investment costs, LNG is considered a cost-effective solution. Retrofitting vessels are in general costly, about 40% higher compared to installing abatement technologies on new builds. Installation is easier in new ships where necessary space can be designed at the planning stage. Thus, having vessels retrofitted for LNG is expensive, especially if single fuel technology is to be installed. The LNG dual fuel technology is a flexible solution, and more economic when trading in areas where the strict emission limits do not apply.

The cost comparison between the different scenarios depends largely on the future development of fuel prices. HFO prices are low and stable; one of the main reasons why the operational costs for scrubber combined with SCR-technology are low. If the LNG fuel price becomes as high as the MGO fuel price, as seen in the "Extreme 2015" fuel price scenario, the present value of total costs will be significantly higher than for the "Normal 2015" fuel price scenario. In that case, MGO is more cost-effective. If the LNG price stays between the HFO price and the MGO price, as for the "Normal 2015" fuel price scenario, however, LNG is still considered cost-effective.

The results from the study show that there is a great reduction potential in emissions from ships. However, marine transportation will get more expensive. Regardless of which compliance strategy a ship owner chooses, the owner faces increased costs, either in form of increased operational costs or in form of investment costs. The strategies that have low investment costs, and seem like the best alternative "right now", could turn out to be quite costly in a long-term perspective.

If the emissions standards are tightened even more in the future, what could become the *most* dominating choice among ship owners is no trade in the ECAs at all. Re-routing of goods to places outside the ECAs, or modal shift to either rail or road could be a consequence. This would have a negative effect on the economy in the North and Baltic Sea area. This issue is not addressed in the case study, but is an interesting additional scenario for further work.

Uncertainty of Results

The two key results in this study are the achieved emission reductions by the abatement measures and the costs for the different scenarios. The main contributors to the uncertainty in the emission and cost results are listed below.

Emissions:

- The assumptions regarding engine operation (engine load, efficiency, days at sea etc.);
- The vessel speed (assumed to be constant);
- The level of maintenance and/or replacement;
- The variation of sulphur content in the fuel; and
- The NO_x emission factor (assumed to be constant).

Costs:

- The investment and installation costs are estimates based on several relevant sources, some more up-to-date than others;
- The level of maintenance and/or replacement;
- The fuel prices are rough estimates;
- The discount rate (assumed to be constant); and
- The additional costs of retrofitting abatement equipment.

Further Work

For further work, one or more of the following should be considered:

- A (more) detailed operational profile with different ECA shares;
- Other possible abatement technologies;
- Accurate information for all technologies concerning costs and emissions;
- Different ship types considered, where the reduced cargo capacity would be an important aspect when considering the different compliance strategies;
- Including emissions of other pollutants like; CO_2, VOC and PM;
- Considering operational measures like; speed reduction, optimization of route etc.; and
- Scenario 4: Modal Shift (?).

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Appendices

A. Pre-Project

Pre-Project

Cost-Efficient Emission Control Area Compliancy

Stine Madsen & Tina Charlotte Olsson

3rd February, 2012

1. Background Information

The information gathered in the project work from the fall of 2011 will serve as a foundation for the rest of the master thesis. A thorough literature study will provide more background information. The following headlines show which subjects that will be included in the further work.

1.1 Emission From Shipping

Shipping is one of the most efficient modes of transportation currently available. The projected growth in shipping due to an expansion in trade is causing an increased environmental concern. Air emissions from ships, in the form of gases such as CO_2, NO_x and SO_x, cause environmental effects that have impact on climate change, local air quality and consequently on nature and health.

1.1.1 Emissions to Air

In the master thesis the focus will be on NO_x and SO_x emissons from ships. There will be a brief description of these pollutants in this section.

1.2 Identification of Measures Which Reduce SO_x and NO_x Emissions From Ships

Abatement technologies can be divided into two main categories, which contains different options.

- Alternative fuels
  - LNG
- Fuel and scavenging air conditioning
  - Scrubber
  - SCR

1.3 Emission Control Areas

Stricter emission requirements, than the global requirements, are regulated in specifically designated geographical areas. In this section there will be a description of the ECA. It will also include the environmental impacts from shipping and the regulations within the areas.

We focus will be on Tier III in Annex VI of the MARPOL Convention when it comes to NO_x emissions.

2. Problem Description

The theme for the master thesis is "Cost-Efficient ECA Compliancy" with a focus on LNG as ship fuel. The goal is to identify and evaluate different abatement measures to comply with the IMOs requirements for a chosen case study.

The purpose is to go in depth with two types of ships/a fleet, and analyze what is the most cost-efficient solution for each ship type. The abatement measures will be complied for both new builds and existing ships. In order to identify the best abatement measure(s), a cost-benefit analysis is to be carried out.

The scope of the project:

1. Choose two different ship types and their operational profile
2. Identify abatement measures
3. Find a method to calculate the cost-effectiveness for each abatement measure in the case study (cost benefit analysis)
4. Use necessary tools for developing a model and calculating the effectiveness of the measures for each ship type

The case study will contain two ship types, ro-ro and container ships, and both new builds and existing ships (retrofitting). The four different case scenarios are explained in chapter 3.

3. Case Study

3.1 Short Sea Shipping

As mentioned in the project work, short sea shipping dominates the trade in the Barents Sea/ECAs, and ro-pax, ro-ro and general cargo have been highlighted as being particularly interesting when it comes to this shipping mode. Ro-pax, ro-ro and general cargo are ships with predictable trading patterns and foreseeable port activity, in contrast to other shipping segments like tanker trading, DMA (2011).

By 2015, vessels operating in (and outside) ECAs will have to reduce their SO_x emissions considerably, as the sulphur limit is being reduced to 0.1%. In addition, the IMOs Tier III requirement will force new build vessels from 2016 to emit substantially reduced NO_x when operating in ECAs.

Switch to LNG, switch to distillate, exhaust gas cleaning (scrubber) and/or Selective Catalytic Reduction (SCR), are technical solutions to the regulatory challenges. SCR is a proven and commercially available technology capable of meeting the IMO Tier III NO_x requirements and is expected to become a standard in shipping [iac (2012)].The abatement measures mentioned can be combined to evaluate 2015 (SO_x) and 2016 (SO_x+ NO_x) compliancy strategies.

3.2 Description of Ship Type and Fleet Size

The following four scenarios will be looked into for both ro-ro and container ships:

- Scenario 1: New build in 2016, scrubber + SCR
- Scenario 2: New build in 2016, LNG
- Scenario 3: Retrofit, scrubber + SCR
- Scenario 4: Retrofit, LNG

Number of vessels will be determined on a later stage, based on either a real or a fictional fleet (information will be provided by Martin Wold, DNV.

3.3 Operational Profile

In order to determine the pollutants emitted for each ship class in each trade, the specific fuel consumption must be known. This can be found from calculations based on the operational profile. The operational profile shows the sailing pattern, the distance and the sailing duration for each ship. In order to determine the operational profile, the following must be known for each ship class in each trade:

- Engine function (main/auxiliary)
- Engine type
- Engine load
- Operational mode (port/transit/ballast/etc.)

The fuel consumption can be calculated by multiplying the specific fuel consumption [g/kWh], with number of hours per year (in each mode) [h], with the installed power [kW], and the engine load [%]. The total fuel consumption for each ship class in each trade is then found by summarizing the fuel consumption for all operational modes.

4. Approach and Methodology

In order to perform a cost-benefit analysis, an appropriate quantitative method will be carried out in the thesis. Currently, the ICAF/CATCH, and MACC methodologies have been looked upon. A more comprehensive literature study will be performed to gather information and knowledge about other alternative methods that can be applied, either directly or for inspiration. Another method, CAST, developed by DNV, may be such a method (information will be provided by Martin Wold, DNV). The purpose of the literature study is to review different methods, and decide which method is most suited for this particular cost-benefit analysis.

In the following chapter, a preliminary proposal is described based on literature given in the previous courses "Risk Analysis and Safety Management of Maritime Transport" (fall 2010) and "Sustainable Ship Design and Operation" (fall 2011).

4.1 Methodology

4.1.1 ICAF

As mentioned in the project work, the ICAF (Implied Cost of Averting a Fatality) methodology is a much-used methodology for studying risk control measures on a common scale. Measures that achieve ICAF values below USD 3 million should be considered as cost-effective and therefore implemented, Kristiansen (2009).

Based on the cost-effectiveness approach for safety, DNV has developed the CATCH (Cost of Averting a Tonne of CO_2-eq Heating) parameter, regarding emissions to air. The marginal abatement cost of a specific measure is the monetary cost of avoiding 1 tonne of emissions through application of that measure. It is the cost of reducing the next unit of emission DNV (2010). The equation for calculating the CATCH parameter is expressed as follows, Eide (2009):

$$CATCH = \frac{\Delta C_i - \Delta B_i}{\Delta E_i} \tag{4.1}$$

Where:

ΔE_i	is the expected reduction of emissions during the expected operational lifetime of a ship due to the implementation of a measure i [tons];
ΔC_i	is the cost of implementing a measure i on a ship [$];
ΔB_i	is the benefit (other than emission reduction) during the operational lifetime of a ship, due to the implementation of a measure i [$].

By the same logic as the CATCH measure, the cost-effectiveness of a SO_x abatement measure can be evaluated:

$$\text{Cost of averting a tonne of } SO_x = \frac{\Delta C_i - \Delta B_i}{\Delta E_i} \tag{4.2}$$

The same applies for a NO_x abatement measure:

$$\text{Cost of averting a tonne of } NO_x = \frac{\Delta C_i - \Delta B_i}{\Delta E_i} \tag{4.3}$$

4.1.2 Costs

The first step in a cost-benefit analysis is to calculate the costs of an abatement measure. The cost side in a cost-benefit analysis is relatively straightforward, as it includes capital costs and operational costs (in brief).

ΔC_i is the cost of implementing a specific measure onboard a vessel, and includes the investment cost and the installation cost. In the cost-benefit analysis, thorough research has to be carried out to find the accurate cost of investments. However, the following information has been given so far in the process Wold (2011):

- The total investment cost for one scrubber unit is 825 + 65 x Engine Power [MW].
- For one unit SCR system installed onboard a vessel with an engine size of 3 MW, the cost is approximately NOK 3 million. With an engine size of 10 MW, the cost will be NOK 7 million.
- The urea in the SCR system will cost 4 NOK/liter and the necessary amount urea to remove 1 kg NO_x is 1.5 liter.
- For LNG installation an estimate for the cost is 700 NOK/kW for large vessels and 12000 NOK/kW for smaller vessels. The cost is applicable for new build. For retrofitting the expenses will be approximately 30-40% higher.

The operational service cost of the measure is the annual cost of maintaining the measure when it is in operation. Different operating costs are:

- Manning costs
- Store and lubricants
- Repair and maintenance
- Insurance
- General costs
- Voyage cost (Fuel price, port charges etc)

The opportunity cost is related to the lost income because of possible reduction in capacity/payload or downtime of ship due to the installation of the measure.

4.1.3 Benefits

ΔB_i is the benefit during the operational lifetime of a ship, due to the implementation of an abatement measure. Health and safety are examples of benefits hard to monetize. Examples of benefits that can be measured in money however, are: energy savings due to less resistance, and economic benefits, such as reduced fuel prices and maintenance costs. The literature study will give further information on how to calculate benefits, other than emission reduction.

4.1.4 Emissions

In a simplified manner, ΔE_i can be expressed as follows:

$$\Delta E_i = E_0 - E_1 \tag{4.4}$$

Where:

ΔE_0	is the pollutant emitted before implementation of measure i [tons];
ΔC_i	is the pollutant emitted after implementation of measure i [tons].

In order to find the expected reduction of emissions, the amount polluted has to be calculated for both states. The emissions can be calculated by use of the following equations, Lindstad (2011):

$$E_p = \sum\nolimits_{fsem} E_{pfsem} \tag{4.5}$$

and

$$E_{pfsem}\left[\frac{g \cdot p}{tons \cdot Nm}\right] = \frac{C_{fsm}\left[\frac{kgfuel}{day}\right] \cdot F_p\left[\frac{g \cdot p}{kgfuel}\right]}{L_{fsem}\,[tons] \cdot V_{fsem}\left[\frac{Nm}{hour}\right] \cdot 24\left[\frac{hours}{day}\right]} \tag{4.6}$$

Where:

p	is the pollutant in question (NO_x/SO_x);
f	is the fuel in use (HFO/MGO/LNG/etc.);
s	is the ship class (Ro-Ro/container);
e	is the ship class (Ro-Ro/container);
m	is the ship class (Ro-Ro/container);
E_p	is the total emissions from pollutant p;
E_{pfsem}	is the emissions from pollutant p from use of fuel f on ship class s with engine type e in operational mode m;
C_{fsm}	is the daily consumption of fuel f in ship class s in mode m;
F_p	is the emission factor for pollutant p from fuel f in engine type e;
L_{fsm}	is the payload carried by ship class s with the use of fuel f with engine type e in operational mode m;
V_{fsem}	is the speed of ship class s with engine type e in operational mode m with the use of fuel f.

ΔE_i will vary with the speed of the vessel, the emission factor and so on. A typical NO_x emission factor for an engine today is 55 [kg NO_x/tons fuel], Wold (2011)

4.1.5 Sensitivity Analysis

After estimating the cost-effectiveness of each measure, a qualitative analysis should be carried out. Different measures have different influences. Based on the values of the cost-effectiveness approach, a sensitivity analysis will be conducted to determine which variables that appear to have the most influence on the outcome of the cost-benefit analysis. In order to limit the uncertainty of the results, better information will be gathered about the values of these variables.

4.1.6 Tools

The goal for the master thesis is to develop a spread sheet based model that allows for simple cost and effectiveness comparison of emission abatement technologies. The main tool for calculating emissions reduction will be Microsoft Excel. Other tools may be identified during the literature study.

5. Time Schedule

5.1 Preliminary Schedule

The Gantt-diagram shows a schedule for the master thesis work. As it is difficult to know how comprehensive each task will be at this stage, the schedule is only tentative.

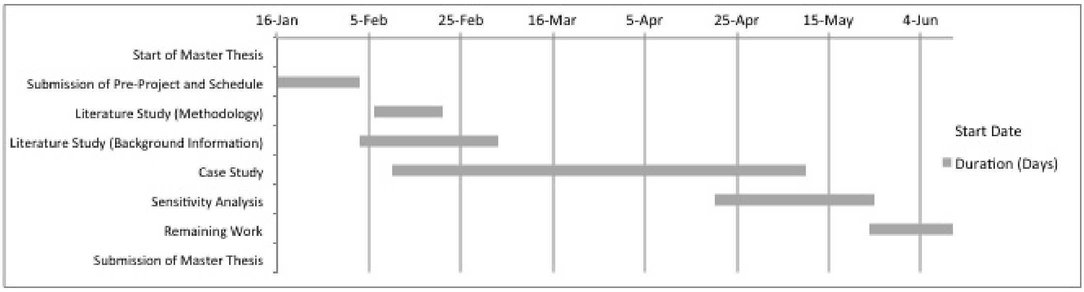

Figure 5.1: Preliminary Schedule

Milestones from the Gantt-diagram:

- 03.02.2012 Submission of Pre-Project and Schedule
- 21.02.2012 Literature Study (Methodology)
- 04.03.2012 Literature Study (Background Information)
- 10.05.2012 Case Study
- 25.05.2012 Sensitivity Analysis
- 11.06.2012 Remaining Work and Submission of Master Thesis