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SDPO.18.014.m

A DECISION-SUPPORT METHOD TO MEET THE EMISSION STANDARDS IN SHIPPING

The case of Seatrade

A decision-support method to meet the emission standards in shipping

The case of Seatrade

by

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to obtain the degree of Master of Science at the Delft University of Technology,
to be defended publicly on Wednesday June 13, 2018 at 10:00 a.m.

Student number:	4508513	
Project duration:	September 4, 2017 – June 13, 2018	
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This thesis (SDPO.18.014.m) is classified as confidential in accordance with the general conditions for projects performed by the Delft University of Technology and cannot be made public until June 13, 2023.

TU Delft

Preface

When finalizing my bachelor's degree at the Maritime Institute 'Willem Barentsz' and receiving my Certificate of Competence for being an onboard maritime officer, the tendency to start working was significant. However, I decided to continue studying in Delft, a key decision in my career which I have never regretted. The study time in Delft improved both my hard and soft skills which will be very valuable for my remaining career. This thesis remarks the completion of the Master program in Marine Technology, conducted in the research group Shipping Management. The subject of this thesis is in the middle of my interest and in line with my bachelor's thesis, for which I conducted onboard emission measurements. The interesting thing of emission compliance is the interrelated combination of many aspects and factors involved in the decision. The commercial aspect was most unknown to me, and it will be for a typical Delft student. Therefore, the gained knowledge and developed proficiency on this side is very useful and a real addition to my master's degree. It helped me to place decision-making in a broader context.

This research would not have been possible without the involvement and support of many people. In particular, I would like to thank Ing. Vincent Peeters and Ir. Michiel Schaap, who were my supervisors from Seatrade. They guided me very well throughout the process and gave me all possibilities within the company to improve the final result. In addition, I would like to thank my colleagues from the Newbuilding department of Seatrade, Ir. Jarek Cisek and Ing. Bert de Boer, who where always willing to help, think along and discuss related and non-related topics. I would also like to thank my supervisors from the university, Prof. Dr. Eddy van de Voorde and Ir. Koos Frouws, for their enthusiastic support and valuable feedback to improve this thesis. Furthermore, I would like to thank Dr. Ir. Henk de Koning Gans for his willingness to be part of my graduation committee and assessing my thesis work.

Special thanks for my parents, Hette and Nancy, who supported me through the time of studying. Without their support this would never have been possible. I would also like to thank the rest of my family, friends and roommates for giving me their support, help and relaxation where possible.

I hope you will enjoy reading this thesis.

Mick van der Meer
Delft, May 2018

Abstract

Due to the increased social importance and regulations on shipping emissions, effort must be made by ship owners, operators and naval architects to reduce the amount of air emissions from ships. A large set of emission control methods exists, but compatibility and interaction issues complicate their implementation, making their selection a non-trivial decision problem. The amount of air emissions to reduce will depend both on the actual emission performance of the ship and the emission targets a ship owners wants to reach or is required to reach. Different ship owners will have different emission targets depending on their operating area and motivations.

The first upcoming emission regulation that shipowners will face is the global limit of 0.5% sulphur that is allowed to be present in the fuel. This regulation will enter into force in 2020 and is a significant reduction, as the global limit before 2020 is 3.5% sulphur. A limit of 0.1% sulphur is already enforced inside Sulphur Emission Control Areas in 2015 and will remain in effect. The limit on NO_x emissions depend on the keel laying date of the ship. Ships with a keel laying date after 1 January 2011 need to comply with Tier II requirements, which can be met by engine modifications. Tier III requirements only apply in Nitrogen Oxide Emission Control Areas for ships with a keel laying date after 1 January 2016. The actual enforcement date varies per Nitrogen Oxide Emission Control Area. The strategy on CO_2 reduction is still in development by the IMO but may also lead to additional abatement costs in due time. The compliance options that are currently technically available at this moment to comply with the SO_x and NO_x regulations are: (1) use low sulphur fuels, (2) install a sulphur scrubber and/or catalytic reduction systems, or (3) use Liquefied Natural Gas as a fuel. While all three alternatives are potential solutions for compliance, they each face operational, technological and economic challenges.

An existing optimization model on the selection of emission compliance methods is adjusted and extended to the case of Seatrade. Something which other models does not always take into account are the time value of money, financing costs, insurance costs, loss of revenue, crewing costs and sludge disposal. The completeness distinguishes the model used in this thesis from the others. Following the model, three case studies have been performed on ships which each characterize typical vessels from the Seatrade fleet. A newbuilding freezer vessel has been considered, which has an exceptional operational profile with long port times and relatively slow service speeds. A to be built specialized reefer containership has been considered, which is typed by short port calls and varying service speeds, caused by fixed port slots. Lastly, an existing specialized reefership has been considered for retrofit.

The results show promising payback times for scrubbers. The nominal payback time for the freezer vessel is found to be 4.0 years. For the containership which consumes a lot more fuel, the payback time is only 2.2 years. The payback period for the specialized reefership is 3.7 years, which is relatively long due to more expensive installation costs for retrofit. The average price spread that is used between high sulphur fuel and 0.5% sulphur distillate fuel is 231 $/T. A difference in lower heating value makes the net benefit even more significant. If there will be opted for the installation of scrubbers, the possible threat of unavailability of high sulphur fuels needs to be mitigated by making long term contracts with bunker suppliers. If Tier III compliance is required, installing a Selective Catalytic Reduction system is preferred above the installation of an Exhaust Gas Recirculation. While the price level of both installations is quite comparable, the Exhaust Gas Recirculation gives a significant disadvantage by a fuel consumption penalty. The fuel switch to LNG is found to be a weak business case, mainly caused by the expensive tank costs and a small price spread between 0.5% sulphur distillate fuel and LNG of 12 $/T, not taking into account the difference in lower heating values. Both newbuilding ships show a payback period that exceeds the lifetime of the ship, which could be reduced if the tank size would be reduced, and thus increasing the bunkering interval. The specialized reefership is not considered for retrofit to LNG, as retrofit will definitely be more complex and more expensive, causing the payback periods to rise further.

The final message from this report to the shipowners is, be well prepared for the new sulphur limits and make a substantiated compliance choice, instead of having a wait-and-see approach and let the time pass.

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List of Abbreviations

BDN	Bunker Delivery Note
Btu	British thermal unit
CAPEX	Capital Expenses
cbft	Cubic Foot
CFC	Chloro Fluoro Carbons
CIRR	Commercial Interest Reference Rate
CO_2	Carbon Dioxide
CO	Carbon oxide
DC	Direct Current
EC	European Commission
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EGCS	Exhaust Gas Cleaning Systems
EGR	Exhaust Gas Recirculation
EIAPP	Engine International Air Pollution Prevention
ESI	Environmental Ship Index
EU	European Union
FONAR	Fuel Oil Non-Availability Report
GHG	Green House Gas
GMT	Greenwich Mean Time
GWP	Global Warming Potential
H_2O	Water
HC	Hydrocarbon
HSFO	High Sulphur Fuel Oil
IAPP	International Air Pollution Prevention
IBOR	Interbank Offered Rate
IMO	International Maritime Organization
IRR	Internal Rate of Return
LHV	Lower Heating Value
LNG	Liquefied Natural Gas

MARPOL	International Convention to Prevent Pollution from Ships
MDP	Markov Decision Process
MEPC	Maritime Environmental Protection Committee
MRV	Measuring, Reporting and Verification
N_2	Dinitrogen
NaOH	Sodium Hydroxide
NCR	Normal Continuous Rating
NECA	NO_x Emission Control Area
NO_x	Nitrogen Oxides
NPC	Net Present Costs
NPV	Net Present Value
O_2	Dioxygen
ODS	Ozone Depleting Substances
OPEX	Operational Expenses
OPS	On-shore Power Supply Installation
PAH	Polycyclic Aromatic Hydrocarbon
PM	Particulate Matter
rpm	rounds per minute
SCR	Selective Catalytic Reduction
SECA	SO_x Emission Control Area
SEEMP	Ship Energy Efficiency Management Plan
SFC	Specific Fuel Consumption
SMS	Safety Management System
SO_x	Sulphur Oxides
SOLAS	International Convention for the Safety of Life at Sea
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
STG	Steam Turbine Generator
SWOT	Strengths Weaknesses Opportunities Threats
TBN	Total Base Number
TEU	Twenty Foot Equivalent Unit
UK	United Kingdom
ULSFO	Ultra Low Sulphur Fuel Oil
ULSGO	Ultra Low Sulphur Gas Oil
UNCTAD	United Nations Conference on Trade and Development

US	United States
VLSFO	Very Low Sulphur Fuel Oil
VLSGO	Very Low Sulphur Gas Oil
VOC	Volatile Organic Compounds
WCU	Water Cleaning Unit
WHRS	Waste Heat Recovery System
WTI	West Texas Intermediate

1

Introduction

The background of this research is given in the first section of this chapter. Next, the research objectives and research scope are introduced. Lastly, an outline of this thesis will be presented which briefly describes the structure of this thesis.

1.1. Background

Shipping emissions are high on the political agenda at this moment. Emissions from ships exhausts into the atmosphere and can potentially be harmful to human health, cause acid rain and may also contribute to global warming [71]. Most ships are currently equipped with a conventional Diesel engine and are burning heavy fuel oil. The composition of the exhaust gases of a conventional Diesel engine are given in Figure 1.1 [88]. There can be concluded that nitrogen oxides (NO_x) and sulphur oxides (SO_x) are the main pollutants. Kuiken [88] does not consider carbon dioxide (CO_2) as a direct pollutant because this emission is not directly harmful to human health. However, this emission is certainly contributing to the Greenhouse effect and is therefore considered as an indirect pollutant.

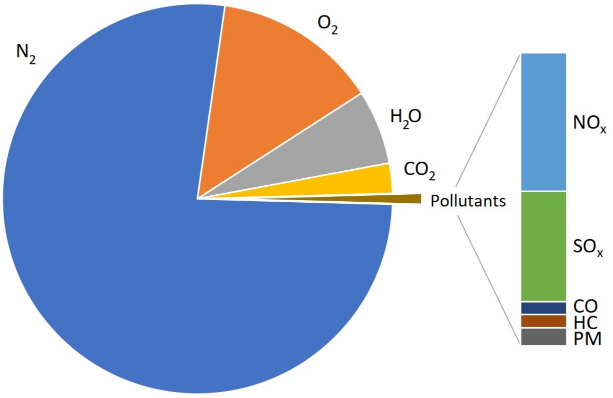


Figure 1.1: Composition of the exhaust gases of a Diesel engine

Currently enforced regulations aim to reduce the direct pollutant emissions SO_x and NO_x. Regulations on CO_2 emissions are currently only efficiency related. However, the ongoing discussions on further CO_2 reductions will result in a new set of targets for the shipping industry in the near future [24]. To meet the SO_x and NO_x emissions, different technical solutions are available without changing the engine configuration of the ship. However, most of these measures are slowing down the transition to low carbon shipping or have a penalty on the efficiency and thus also on CO_2 emissions [24]. The selection of emission control methods can be a complex decision given the uncertainties related to future regulations, fuel availability and technology development. From the perspective of the authorities that develop the regulations, it is important that any new regulations are realistic and transparent, to avoid penalizing the owners who have invested in certain solutions before the CO_2 strategy was decided.

Due to the increased social importance and regulations on shipping emissions, effort must be made by ship owners, operators and naval architects to reduce the amount of air emissions from ships. A large set of emission control methods exists, but compatibility and interaction issues complicate their implementation, making their selection a non-trivial decision problem [11]. The amount of air emissions to reduce will depend both on the actual emission performance of the ship and on the emission targets a ship owners wants to reach or is required to reach. Different ship owners will have different emission targets depending on their operating area and motivations [10]. Several large ship owners gave recently insight in their emission reduction strategy [138] [154] [113]. From these insights, there can be concluded that the strategy is not so straight-forward and that the different choices of the companies may not be necessary wrong for one or another ship-owner, due to fleet differences.

It is difficult to estimate how fast the technology in the shipping industry will develop. That is one reason why most ship owners are very cautious with respect to investments in new technology. Ship owners want to avoid the scenario that they are investing in a cleaner ship and after a few years, the technological development might be already outdated. By this research, the risks of investments with respect to payback time, fuel prices and other factors can be demarcated and become insightful.

1.2. Objectives

The objectives of this research project can be formulated as listed below and indicate the different steps that will be taken in this research to obtain the final result, a generic cost effective life-cycle strategy which can be applied to all ships of the Seatrade fleet. The research objectives are:

- Identify which emission reduction requirements must be met by ship-owners and which emission control methods are technically available at this moment.
- Select a generic decision-support methodology in order to develop a cost effective strategy for the life-cycle of a ship in order to meet the emission regulations. Adjust and extend the methodology to the Seatrade case.
- Implement the generic methodology into a tool that can be used by Seatrade to develop the life-cycle strategy of a particular ship.
- Perform case studies to get insight in the effects of the investments in different compliance options.
- Obtain an indication of the cost effective life-cycle strategy of the Seatrade fleet.

1.3. Scope

This study will focus on the development of a decision-support method in order to define the most cost effective life-cycle strategy. The decision-support method can be applied to an arbitrary ship of the Seatrade fleet and can be used as initial analysis to the financial feasibility of a particular compliance method. The model need to be accessible and the time required to set up a case study should be minimized. The disadvantages of an accessible generic method are limited accuracy and to a certain extent, incompleteness. Therefore, a trade-off between accessibility and completeness should be made and the disadvantages should be minimized.

The model need to be used to support a decision on which emission compliance method to use. The most important objective is to get insight in the effects of an investment on the economics. This means that the focus need to be on the effects of the investments. The model does not need to include the complete financial performance of a ship but should be limited to those parameters and factors that vary for different compliance options. The expenses and earnings that are constant for all compliance options are not taken into account and are outside the scope. The model does also not need to obtain the best possible moment to invest but has to show the effects of an investment in a prescribed year. This is especially applicable if an abatement technique has a limited lifespan. In this case, the effects on doing the investment in a prescribed year need to be considered. The effects of repeating the same investment another time after the lifespan has expired does not need to be included. This scenario requires a new analysis at the time the next investment is considered. An example of such a case is when a scrubber has a lifespan of 15 years, while the ship has an operational lifetime of 30 years. Then, the effects on investing right now in a scrubber need to be considered. The second part of the lifetime of the ship, the yearly costs need to be calculated as if the scrubber is not installed anymore. Another investment need to be done to let the ship operate for another 15 years with a scrubber, which requires a new analysis at the time when the investment is done.

1.4. Outline

This chapter introduced the topic and context of the research. The research objectives are given, which can be revert back to in the intermediate and final conclusions. In the scope, the extent of the subject matter that is dealt with is discussed. Chapters 2 and 3 together form the literature study on the current state of emission legislation and compliance methods. Chapter 2 covers the legislation that is applicable to this study. The majority of the applicable legislation is set by the International Maritime Organization (IMO). However, some legislation is enforced by local authorities. Chapter 3 includes the compliance options that are technically available or that are expected to become available in the near future in order to comply with the legislation as discussed in Chapter 2.

The appropriate approach for selection of the difference compliance methods will be defined in chapter 4. A conceptual framework will be represented, which will form together with the methodology a substantiated base of the optimization model. The actual model will be shown in Chapter 5, which gives a mathematical definition of the optimization model, including the objective function and constraints.

Chapter 6 gives the results of a market analysis and places this research in a broader context. The current uptake of scrubbers and LNG is discussed and a reflection to the future is presented based on actual orders. A fuel price scenario is presented based on historical data and future expectations on the long term. This fuel price scenario will be used in the case studies. A SWOT analysis is performed to get insight in the strengths and weaknesses of the different compliance methods, placed in a market perspective. Lastly, the position of Seatrade in market perspective is discussed.

In chapters 7, 8 and 9, the model as described in Chapter 5 will be applied to three different ships of Seatrade. The first and second case will be performed on a ship that is currently in the design phase. In the design phase, arrangement are expected to be easily adjustable and space requirements are to a lesser extent an issue. The third case will be performed on a relatively new ship, which still has a significant remaining lifetime. Chapter 10 concludes the thesis with an evaluation of the research objectives. Conclusions and recommendations that arose from this research are given in this chapter.

Several appendices are attached to underset the content of this thesis. Appendix A gives a brief introduction of shipping finance, for those readers that are not acquainted to the different finance sources in shipping. Appendix B gives an impression of the tool that is made for Seatrade in order to perform the case studies. Appendices C till K give more detailed data related to the case studies. Of each case study, an elaboration of the input data, results and sensitivity analysis is given. Appendix L gives a comparison of the results of the case studies with respect to other researches in order to validate the results. Appendix M gives a list of specialists that are contacted in the course of this research. A paper is added in Appendix N, which shows the results of a sensitivity analysis on the payback periods of different compliance options. The paper is an extension of this thesis, as this thesis is more focused on the sensitivity of the Net Present Costs instead of the payback periods.

2

Legislative background

The global legislation for ships is issued by the IMO. The base of the legislation related to shipping emissions is made in the International Convention to Prevent Pollution from Ships (MARPOL), which is applicable to all ships flagged under countries that are signatories to the MARPOL convention. In addition to this convention, several codes and guidelines are adopted. These codes and guidelines include regulations applicable to only a specific emission, fuel or compliance method. It is important to gain insight in the legislation before considering the control methods, because control methods that are eliminated by the legislation does not have to be considered.

2.1. Regulations

The IMO began examining ships' air pollution via the Maritime Environmental Protection Committee (MEPC) in 1988. As a consequence, a new air pollution addendum to MARPOL 73/78 was adopted in 1997 [56]. The new addendum, Annex VI, limits the airborne emissions from ships (SO_x, NO_x, ODS, VOC, shipboard incineration) and their contribution to local and global air pollution and environmental problems. However, this thesis will be limited to the emissions as a direct result of the combustion engines used for propulsion and power generation and will not include the provisions for vapor collection systems and restricted use of CFC refrigerants.

MARPOL 73/78/97 was revised in 2008 with the aim of significantly strengthening the emission limits in light of technology improvements and implementation experience. The revised Annex VI includes a three-tier approach to control NO_x emissions and a three-phase implementation for the control of SO_x emissions. The revised Annex VI entered into force on 1 July 2010 [73].

The approach of the IMO is not to regulate in favour of any energy source or technology, but to set efficiency targets and leave the choice of which compliance methods to use to the industry [158]. This is mainly reflected in the requirements on CO_2 emissions. In July 2011, new amendments of MARPOL Annex VI were adopted in which two mandatory mechanisms, the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) are included to ensure an energy efficiency standard for ships [73]. This new amendment entered into force on 1 January 2013 [58]. Besides these short-term measures on CO_2 emissions, the IMO will shortly adapt a long-term strategy on Green House Gases (GHG), which will be discussed in more detail in Section 2.1.4.

Regulation 3 of MARPOL Annex VI provides exemptions for compliance to any emission reducing regulation, necessary for the purpose of securing the safety of a ship or saving life at sea or any emission resulting from damage to a ship or its equipment provided that all reasonable precautions have been taken after the occurrence of the damage or discovery of the emission for the purpose of preventing or minimizing the emission. This exemption does not apply if the owner or the master acted either with intent to cause damage, or recklessly and with knowledge that damage would probably result [73].

2.1.1. Nitrogen oxides

The global rules related to NO_x emissions are described in Regulation 13 of MARPOL Annex VI [73]. The requirements in this regulation apply to each Diesel engine with a power output of more than 130 kW which is installed on a ship, constructed or major converted on or after 1 January 2000. The regulation does not apply to engines intended to be used solely in case of emergency [73]. The rules described in Regulation 13 have set step-wise reductions in global and regional NO_x emissions. The reductions apply in different levels (Tiers) of control based on the construction date of a ship. Within any particular Tier, the actual limit is dependent on the engine's rated speed (n) in rpm as given in Table 2.1.

Table 2.1: Allowable NO_x emission limits

		Total weighted cycle emission limit (g/kWh)		
Tier	***Ship construction date (on or after)***	***n < 130***	***130 ≤ n < 2000***	***n ≥ 2000***
I	1 January 2000	17.0	$45 \cdot n^{-0.2}$	9.8
II	1 January 2011	14.4	$44 \cdot n^{-0.23}$	7.7
III	1 January 2016	3.4	$9 \cdot n^{-0.2}$	2.0

Global Tier I limits are applicable to Diesel engines installed on ships constructed from 1 January 2000 to 1 January 2011. Global Tier II limits apply to marine Diesel engines installed on or after 1 January 2011. The Tier III standards entered into force on 1 January 2016 and apply only to the specified ships while operating in NO_x Emission Control Areas (NECA) [73]. Outside such areas, the Tier II limits apply. The Tier limits are illustrated in Figure 2.1.

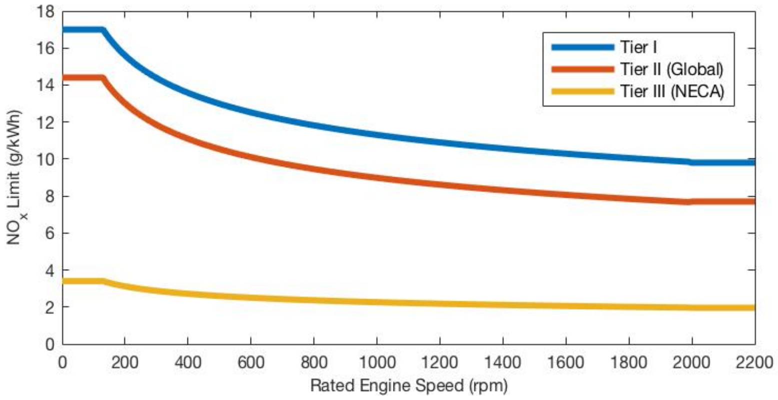


Figure 2.1: Allowable NO_x emission limits

2.1.2. Sulphur oxides

The global rules related to SO_x emissions are described in Regulation 14 of MARPOL Annex VI. The SO_x emissions are proportional to the sulphur content of the fuel [160], therefore Regulation 14 prescribes limits on the sulphur content of the fuel. Similar to the limits on NO_x, these limits are step-wise implemented. Distinction is made between waters inside SO_x Emission Control Area (SECA) boundaries and waters outside those boundaries. In contrast to the NO_x regulations, which are applicable to new-builds only, the SO_x regulations are applicable to all ships [73]. The sulphur limits as prescribed in Regulation 14 are listed in Table 2.2 and illustrated in Figure 2.2.

Table 2.2: Allowable sulphur content in the fuel

	Sulphur limit in fuel (% m/m)	
Implementation date	***Global***	***Inside SECA***
1 January 2000	4.5%	1.5%
1 July 2010		1.0%
1 January 2012	3.5%	
1 January 2015		0.1%
1 January 2020	0.5%	

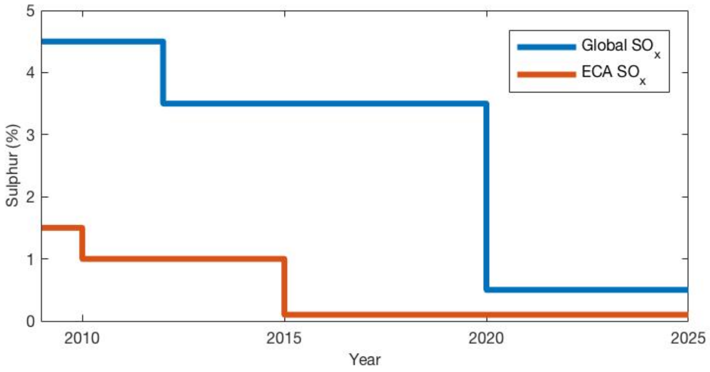


Figure 2.2: SO$_x$ emissions IMO legislative timescale

To confirm compliance with Regulation 14, ships are required to maintain and have available:

- Bunker Delivery Notes (BDN).
- Fuel oil samples, taken at the time of fuel oil delivery.
- Fuel oil changeover procedures to show that the changeover is initiated in time before entering the SECA.
- The logbook that contains the volume of fuel oil in each tank and the date, time and position of the ship when any fuel oil changeover operation is completed prior to entry into or commenced after exit of a SECA.

Fuel can be non-compliant before it is bunkered, due to a failing by the supplier, or fuel can be non-compliant when on board, due to failings in the operational fuel handling on the ship. There are guidelines to check for the former but not the latter. If fuel is found to be non-compliant by failing by the supplier, the Port State is required to take action against the supplier. The Flag State and the IMO must be informed that the fuel supplier has failed to meet the requirements [158]. If fuel is found to be non-compliant due to operational fuel handling, it is the task of the Port State Control to take appropriate measures.

The use of compliant fuel is not the only way to comply with the SO$_x$ regulations. This is provided by Regulation 4 where is stated that other compliance methods used as alternative to that required by Annex VI may be allowed by the Flag State if they are at least as effective in terms of emission reductions [73]. This means that both inside and outside SECAs, approved abatement technologies can be used to reduce SO$_x$ emissions. Currently, the only approved abatement technology related to SO$_x$ emissions is the application of Exhaust Gas Cleaning Systems (EGCS). The use of EGCS is only permitted when meeting the Guidelines for EGCS, as will be described in Section 2.2.3.

2.1.3. Particulate matter

Legislation is currently regulating the emissions of the secondary PM precursors, such as SO$_x$ and NO$_x$ [158]. There are no specific regulations that directly limit primary PM emissions from sea-going ships. Regulation 14 of MARPOL Annex VI regulates SO$_x$ and, as a consequence secondary Particulate Matter (PM) emissions. However, the reduction of these PM emissions is not quantified.

2.1.4. Carbon dioxide

The EEDI and the SEEMP are two measures that are already in place since 1 January 2013 to reduce CO$_2$ emissions. The EEDI is applicable to new ships and is a performance-based mechanism that demands a minimum energy efficiency in new ships [58]. Ship designers have the possibility to choose the most appropriate technologies to meet the EEDI requirements for a specific ship design. The SEEMP sets out a procedure for operators to improve the energy efficiency of ships and is applicable for both newbuilding and existing ships.

Regulation 21 with respect to the EEDI states that smaller size vessels are excluded from having a required EEDI. The size limit is referred to as cut off levels. The EEDI will be implemented in different phases, which are illustrated in Figure 2.3.

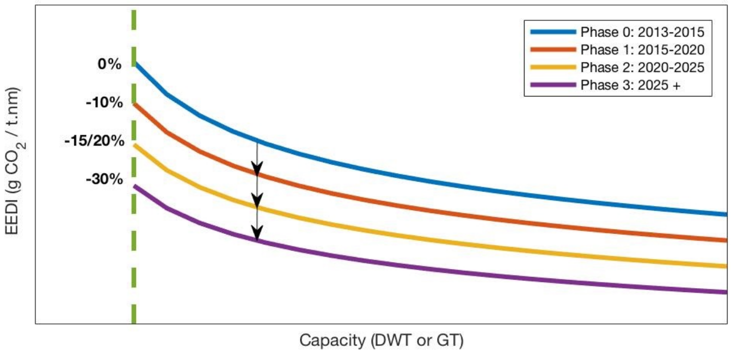


Figure 2.3: EEDI phases

The EEDI reference line has ship type specific parameters and has the general form:

$$Reference\ EEDI = a * b^{-c} \tag{2.1}$$

Where b represents the ship capacity and a and c are constants agreed for each ship type and included in the regulation. The reduction factor for each phases is dependent on the building year of the ship and is also included in the regulation.

The attained EEDI is the actual value of the EEDI for a ship and represents the amount of CO_2 generated by a ship in one ton-mile. A simplified version of this equation is given in equation 2.2, where SFC represents the Specific Fuel Consumption of the ship, C_F the carbon factor for the fuel and DWT the deadweight of the ship [66].

$$Attained\ EEDI = \frac{CO_2\ emissions}{transport\ work} = \frac{Engine\ power \times SFC \times C_F}{DWT \times speed} \quad (g\ CO_2\ /\ t-nm) \tag{2.2}$$

Regulation 22 with respect to the SEEMP states that each ship is required to keep a SEEMP on board, which may form part of the ship's Safety Management System (SMS). The SEEMP should be written in a working language understood and accessible for the ship's crew. The purpose of the SEEMP is to improve the energy efficiency of the ship during its lifetime. The guidance on the development of the SEEMP for new and existing ships incorporates best practices for fuel efficient ship operation, and as well guidelines for voluntary use of the Energy Efficiency Operational Indicator (EEOI) [64]. The EEOI enables operators to measure the fuel efficiency of a ship in operation and to gauge the effect of any changes in operation, for example the application of Waste Heat Recovery Systems or more frequent propeller cleaning.

As part of the long-term strategy on CO_2 emissions, the IMO adopted a mandatory fuel consumption data collection system for CO_2 emissions from shipping in October 2016, which is seen as a precursor to the development of additional CO_2 reduction measures. The system is primarily based on fuel consumption and should be simple for ships to administer [60]. The aggregated data will be reported to the Flag State and the Flag State will issue a Statement of Compliance to the ship. Flag States will subsequently transfer the data to an IMO Ship Fuel Oil Consumption Database. The data collected will provide a basis on which future decisions on additional measures can be made.

The data collection system is the first step of a step-wise implementation of CO_2 reduction measures in shipping. The three-step approach consists of the following steps:

- Step 1: Data collection.
- Step 2: Data analysis.
- Step 3: Decision-making on what further measures, if any, are required.

The data collection system is part of a roadmap from 2017 to 2023 that is focused on developing a comprehensive strategy for the reduction of GHG emissions from ships. It foresees an initial GHG strategy to be adopted in 2018 [70]. It contains a list of activities and further IMO GHG studies with relevant timelines and provides for alignment of those new activities with the ongoing work by the MEPC on the three-step approach to ship energy efficiency improvements.

Similarly, the European Commission (EC) proposed a strategy for integrating maritime emissions into the policy of the European Union (EU) for reducing its GHG emissions, described in the EU Measuring, Reporting and Verification (MRV) regulation. This strategy was adopted by the European Parliament in April 2015 and came into force in July 2015 [39]. It requires ship owners and operators of ships calling any EU port to annually measure, report and verify CO_2 emissions. For every vessel that anticipates making a commercial call in an EU port, a monitoring plan must be developed. In particular, the monitoring plan must specify which of the four emission monitoring methodologies (BDN and periodic stock-takes of fuel tanks, bunker fuel tank monitoring, flow meters or direct emission measurement) the shipping company intends to use [39].

Both the IMO and the EU have the ambitions to reduce GHG emissions from ships, and have strategies to achieve their goals. Although there are some differences between both systems. The approach of the IMO requires only the fuel consumed, where the EU MRV regulation requires reporting of fuel consumed, actual cargo carried onboard and CO_2 emitted. The IMO will make the raw data only available to the Flag States who will then share aggregated anonymised data, while the EU will make this information publicly available. The system of the IMO will be enforced on 1 January 2019, while the system of the EU MRV regulation is already enforced on 1 January 2018.

2.2. Codes and guidelines

Several codes and guidelines are adopted to specify additional requirements on a specific emission, fuel or compliance method. The NO_x Technical Code is related to Regulation 13 of MARPOL Annex VI concerning NO_x emissions. The NO_x Technical Code provides the procedure and calculation methods to prove compliance with this regulation. If Selective Catalytic Reduction (SCR) is used as abatement option for NO_x compliance, additional guidelines apply to the application of those systems. If EGCS are used for compliance with Regulation 14 of MARPOL Annex VI, the Guidelines for Exhaust Gas Cleaning Systems apply. These guidelines are adopted to ensure the quality and effectiveness of this abatement option [158]. When gas is used as a fuel, the ship is subject to International Code of Safety for Ships using Gases or other Low-flashpoint Fuels, also referred to as the IGF Code. This code aims to minimize the risk to the ship, its crew and the environment, having regard to the nature of the fuels involved [68].

2.2.1. NO_x Technical Code

The Tier II and Tier III limits, as discussed in Section 2.1.1, needs to be certified in accordance with the revised NO_x Technical Code 2008. Tier I engines have been certified to the earlier, 1997 version of the NO_x Technical Code. Certification issued in accordance with the 1997 NO_x Technical Code would still remain valid over the service life of such engines [65]. The purpose of the Technical Code is to specify the requirements for testing, survey and certification of marine Diesel engines to ensure they comply with the NO_x emission limits of Regulation 13 of Annex VI. Test cycles and measurement methods are used to determine the total emission of NO_x, calculated as the total weighted emission of NO_2, are specified in the Technical Code. Distinction is made between constant-speed main propulsion engines, propeller-law-operated main/auxiliary engines, constant-speed auxiliary engines and variable speed, variable-load auxiliary engines [74].

To avoid certification testing of every engine for compliance, two approval concepts can be adopted, namely the Engine Family or the Engine Group concept. The Engine Family concept may be applied to any series produced engine which through their design are proven to have similar NO_x emission characteristics, are used as produced, and, during installation on board, require no adjustments or modifications which could adversely affect the NO_x emissions. The Engine Group concept may be applied to a smaller series of engines produced for similar engine application and which require minor adjustments and modifications during installation or in service on board. The certification process includes an emission test for compliance with the NO_x requirements on the manufacturer's test bed. This leads to the issue of an Engine International Air Pollution Prevention (EIAPP) Certificate. Once the EIAPP Certificate is issued, the vessel is ready for IAPP initial survey according to Regulation 13 of Annex VI [73].

In the NO_x Technical Code, three different onboard NO_x verification methods are listed, that are initially decided by the engine manufacturer and specified in the technical file to ensure that engines remain compliant after shipboard installation:

- Engine Parameter Check - to ensure that engine's components, settings and operating values have not deviated from the specifications in the engine's technical file.
- Simplified Measurement - during full load operation of the engine, the NO_x content of the exhaust will be measured.
- Direct Measurement and Monitoring - an onboard measurement device will be installed to continuously monitor the NO_x emissions.

2.2.2. Guidelines for Selective Catalytic Reduction

In the NO_x Technical Code, a special reference is made to Selective Catalytic Reduction (SCR), because it is considered as the most common way in which the Tier III NO_x limits are to be met [107]. Ships fitted with a SCR method to comply with Regulation 13 of MARPOL Annex VI need to fulfill the requirements set in the '2011 Guidelines adressing additional aspects to the NO_x Technical Code 2008 with regard to Particular Requirements related to Marine Diesel Engines fitted with Selective Catalytic Reduction Systems' [63]. Requirements described in these guidelines are in addition the NO_x Technical Code and related to design, testing, surveys and certification.

Two test procedures are possible to demonstrate compliance with Regulation 14 of MARPOL Annex VI. Test scheme A requires a combined shop test of the engine and SCR system together. Emission and performance measurements are done in both Tier II and Tier III modes. This method does not require confirmation of performance when the combination is installed onboard. It only requires a parameter check. At test Scheme B, modeling calculation and model test shall be done before the performance validation test. The engine and SCR are tested apart from each other and need confirmation of SCR performance on the sea-trials at different engine loads [48]. In general, engine systems fitted with SCR systems should be tested on a testbed according to Scheme A. Only in cases where combined engine/SCR systems can not be tested on a test bed due to their size, construction and other restrictions, the procedures provided by Scheme B are applied [7].

When SCR uses an urea solution, ammonia solution or ammonia gas as reductant, measures to prevent reductant slip should be provided to avoid the supply of an excessive amount of reductant in the system. The reductant injection system should be designed to prevent emissions of any harmful substance from the system [7].

2.2.3. Guidelines for Exhaust Gas Cleaning Systems

EGCS are currently the only approved abatement technologies, other than low sulphur fuels, to meet the SO_x regulations. The use of EGCS is only permitted if meeting the Guidelines for EGCS [67]. The Guidelines for Exhaust Gas Cleaning Systems are set to specify the requirements for the testing, survey, certification and verification of EGC systems [67]. The guidelines permit two schemes:

- Scheme A: Unit certification with parameter and emission checks.
- Scheme B: Continuous emission monitoring with parameter checks.

The Guidelines for Exhaust Gas Cleaning Systems include SO_2 (ppm) / CO_2 (% v/v) emission ratios relating to the various levels of sulphur-in-fuel stipulated under the revised MARPOL Annex VI [158]. For a given consumption of carbon during combustion, there is a consumption of sulphur that is proportional to the sulphur content of the fuel. There is a constant ratio between carbon and sulphur adjusted for the molecular weight of oxygen from combustion. The calculations for distillate fuels are slightly different compared to residual fuels due to the different H:C ratios of the two fuels, this is illustrated in Figure 2.4. It can be concluded from this figure that for fuel sulphur levels less than 3.0 % sulphur, the difference in S/C ratios between distillate and residual fuel is less than 5.0 %.

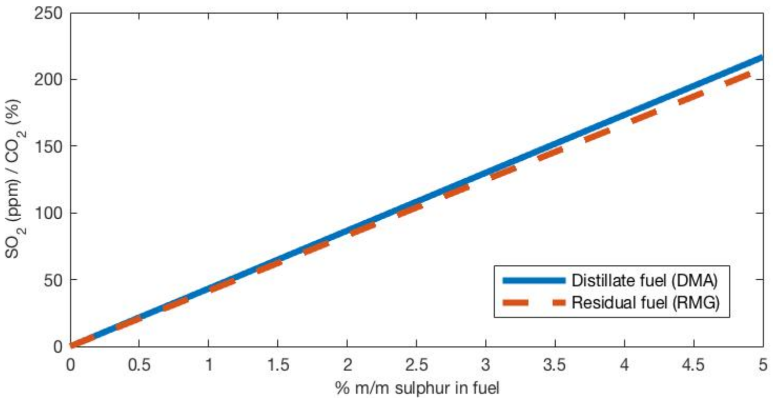


Figure 2.4: SO_2 / CO_2 ratio vs % sulphur in fuel

An assessment of the washwater is required for those EGCS technologies which make use of chemicals, additives, preparations or create relevant chemicals in situ. When the EGCS is operated in ports, harbours, or estuaries, the washwater monitoring and recording should be continuous. The values monitored and recorder should include pH, Polycyclic Aromatic Hydrocarbons (PAH), turbidity and temperature. In other areas, the continuous monitoring and recording equipment should also be in operation whenever the EGCS is in operation, except for short periods of maintenance and cleaning of the equipment. The discharge water should comply with the limits specified in the Guidelines for Exhaust Gas Cleaning Systems with respect to pH criteria, PAH's, turbidity / suspended Particulate Matter, nitrates, washwater additives and other substances [67].

2.2.4. Code for Ships Using Gases or Other Low-flashpoint Fuels

The International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF Code) is an amendment to the International Convention for the Safety of Life at Sea (SOLAS), enforced on 1 January 2017. It requires new ships using gases or other low-flashpoint fuels to comply with the mandatory provisions for the arrangement, installation, control and monitoring of machinery, equipment and systems using low-flashpoint fuels, focusing initially on LNG [97]. Examples of additional requirements are the location of the fuel tanks, gas-tight enclosed fuel pipings, maximum fuel pressure and thermal insulation [69].

Parallel to the IGF Code, new amendments to the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) are enforced. These amendments are related to the IGF Code and include training and qualifications of personnel working on ships using natural gas as fuel [68]. It requires a basic training for all seafarers responsible for designated safety duties associated with the care, use and emergency response of the fuel on board ships subject to the IGF code. For masters, engineering officers and all personnel with immediate responsibility for the care and use of fuels and fuel systems, an additional advanced training is required [72].

2.3. Emission Control Areas

Emission Control Areas are specific areas of coastline and bodies of water in which there are set limits for the emissions of SO_x and NO_x pollutants from exhaust under MARPOL Annex VI. As covered in Section 2.1.2, the legislation applicable in SECAs is not a strict fuel rule. It allows for equivalence methods. In California waters, the California Ocean-Going Vessel fuel rule is applicable besides the SECA legislation. This rule does not allow for equivalence and only the use of low sulphur fuel offers compliance [158]. As from 1 January 2021, the Baltic Sea and North Sea will also become a NECA.

If new NECAs are implemented, the NO_x Tier III requirements will not be retroactive. Thus, if new NECAs take effect, the Tier III emission limits become applicable to vessels with keel-laying as of the date the new NECAs go into effect. This is the case for the Baltic & North Sea NECA that will only be effective for ships with a keel-laying date as of 1 January 2021 [161].

Two SECAs are enforced in the Baltic Sea and North Sea as illustrated in Figure 2.5. As from 1 January 2021, the Baltic Sea and North Sea will also become a NECA.

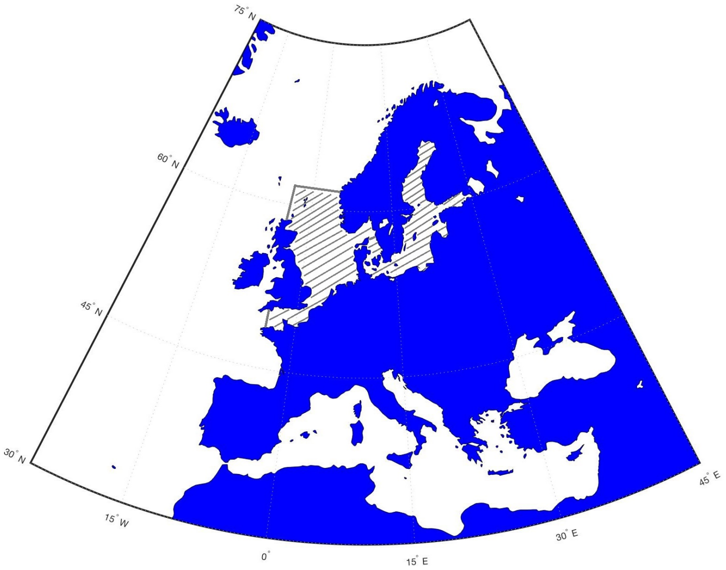


Figure 2.5: Baltic & North Sea ECA

The North American ECA and the United States Caribbean Sea ECA, represented in Figure 2.6, are both designated as a SECA and NECA.

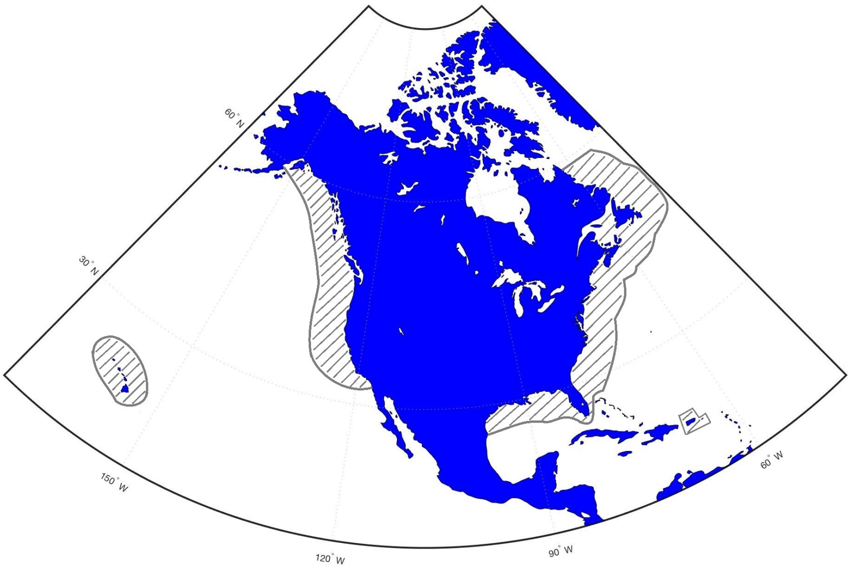


Figure 2.6: North American & US Caribbean ECA

2.4. Conclusion

Shipping currently operates under a complex set of regulations, codes and guidelines. The leaps in regulations are event driven, all having a major impact on the business of the shipping companies. This chapter has gained insight in the legislation and defines a threshold for the remainder of this thesis. Is has become evident that the approach of the IMO is not to regulate in favor of any technology or energy source. This means that there is no proposed optimum compliance method prescribed by the IMO to meet the emission regulations but it is left to the ship owners to find the best way to meet those targets, which is quite a challenge. It is even more challenging because some of the upcoming regulations in the near future are still under development, such as those on CO_2 emissions. The base of these regulations has been set by the introduction of the EEDI and SEEMP, but will be extended in the future. The IMO and EU are currently developing a comprehensive strategy for the further reduction of GHG emissions from ships, including CO_2. Regulations on NO_x emissions are especially challenging inside the NECAs, where Tier III applies and a reduction of approximately 80% is required. SO_x regulations require a reduction of the sulphur content in the fuel, or other approved measures that have at least the same effect. The latest step in the transition to low sulphur bunkers will come into effect in 2020 when globally a sulphur limit of 0.5% is enforced. The fast developments on emission regulations indicate that there is a large transition ahead, making the shipping industry sustainable for the future. The compliance methods that will be considered next has to meet the minimum emission standards described in this chapter.

3

Compliance options

There are various technologies that can be used to reduce the emissions to the limits of the MARPOL Annex VI. Each technology has their own advantages and disadvantages. Distinction is made between methods that reduce the emissions at the source of the pollutants before they arise, called primary control methods, and methods that reduce the emissions after they arise, called secondary control methods.

There is no one-size-fits-all solution, the best option depends upon different factors, including but not limited to vessel type, deadweight, investment costs, operational areas, fuel availability and fuel prices [53] [31]. For options requiring a retrofit, also off-hire, lifetime of the ship and complexity of the installation must be considered. This will be discussed in Chapter 5.

3.1. Primary control methods

The primary control methods that are considered in this section are alternative fuels and adjustments of the combustion process. Both methods influences emissions at their source. The regulations from MARPOL Annex VI are clear in that the default means of SO_x compliance is to use fuel with a low sulphur content and that this is the primary compliance option [96]. There has been arrived a wide variety of fuels with a low sulphur content in the market since the introduction of the 0.1% sulphur limit inside SECAs. A key differentiator of the fuels is whether or not the fuel need to be kept heated in ships' fuel tanks and during transfer onboard. This criteria could be used to determine whether a fuel should be classified as a residual fuel, in case it need heating, or as a distillate fuel, in case is does not need heating [36]. The need of heating for residual fuels is in fact the result of longer carbon chains [88]. Secondly, to separate between fuels meeting a 0.1% sulphur limit and fuels meeting a 0.5% sulphur limit, the terminology should be different. Although there is no distinction specified in the ISO 8217 standards for quality specifications of marine bunker fuels, common used terminology in the industry is ULSFO for Ultra Low Sulphur Fuel Oil, residual fuel with a sulphur limit of 0.1%, VLSFO for Very Low Sulphur Fuel Oil, residual fuel with a sulphur limit of 0.5%, ULSGO for Ultra Low Sulphur Gas Oil, distillate fuel with a sulphur limit of 0.1% and VLSGO for Very Low Sulphur Gas Oil, distillate fuel with a sulphur limit of 0.5%.

ULSGO is widely used since 2015 inside SECAs to meet the SO_x limits as specified in MARPOL Annex VI. As of 2020, the use of VLSGO is very attractive due to the compatibility of the fuel but may not be competitive due to the price difference and availability in comparison with other fuels. Besides the possibilities to use conventional oil-based fuels, the use of Liquefied Natural Gas (LNG) has recently gained more attention and has the potential of being a cleaner fuel. However, LNG is also a fossil energy source and will not be the solution forever. Sustainable energy sources that have the potential to replace fossil fuels in shipping are biofuels and hydrogen [111]. The latter in combination with fuel cells.

NO_x emissions are mainly influenced by the temperature and oxygen concentration in the combustion process. A fuel change to LNG would influence these parameters in a positive way. Hydrogen in combination with fuel cells does not have a combustion process and therefore would completely eliminate NO_x emissions. If sticking to fuel oils, engine modifications and operational set-up can be used to achieve Tier I and Tier II compliance, but other compliance methods are required to achieve Tier III compliance [35]. The one and only primary compliance method for Tier III that is currently used in shipping is the application of Exhaust Gas Recirculation (EGR) .

The change-over to either low sulphur bunkers and LNG and the application of engine modifications and operational set-up are primary control methods that are already feasible in the shipping industry and are seen as short-term solution [129]. The use of biofuels and hydrogen are potential medium- and long-term alternatives because these fuels are not fossil [129]. Other medium- and long-term solutions, including batteries, nuclear propulsion or solutions using wind and solar energy, will not be discussed in this section due to their technical related restrictions and/or limited application in the marine industry at this moment.

3.1.1. Ultra Low Sulphur Fuels

ULSFO is a compliance method that is specially designed to help operators to comply with 0.1% sulphur limits. ULSFO has a low sulphur content, like ULSGO, but has a higher flash point and higher viscosity, similar to High Sulphur Fuel Oil (HSFO) with a sulphur content of 3.5% [2]. The use of ULSFO simplifies fuel changeover procedures, necessary when using ULSGO, to enter areas with emissions control requirements. A disadvantage of ULSFO is that the fuel is highly paraffinic. Compatibility and storage time is reduced and might be an issue.

ULSGO is widely used and has a few limitations. The refining process reduces the aromatic content and density of the fuel, resulting in a decrease in energy content by one percent on a volumetric basis [3]. For ships with engines originally designed to use HSFO, design modifications on the fuel systems and operational adjustments may be needed to ensure the safe and efficient operation of engines and equipment using ULSGO [99]. Distillate fuels have a different flashpoint and viscosity compared to residual fuels. Fuel pumps may need to be replaced due to reduced fuel oil viscosity and lubricity. Additionally, a cooler may be needed in the fuel system to control temperature and maintain viscosity of the fuel [3]. However, ships operating inside SECAs have already (partially) done this modifications. Ships currently operating inside SECAs need to have two separate fuel oil systems to ensure compliance of the 0.1% sulphur limit inside SECAs. If either ULSGO or ULSFO is used as compliance method for the global sulphur limit of 0.5% sulphur, two separated fuel oil systems are not required anymore. This might become an option when the price difference between ULSGO/ULSFO and VLSGO/VLSFO becomes negligible small or if the latter fuels are not available.

The difficulty of the success of ULSGO and ULSFO will lie in the price development, which is unpredictable due to availability of the fuel in the future [78]. According to the research of CE Delft, supply and demand are balanced globally but regional surpluses and shortages are projected to occur, which may lead to significant price differences. In the most cases the Middle East has an oversupply, while in some cases other regions have a higher production than consumption as well. Regional imbalances can be addressed by transporting fuels or by changing vessels' bunkering patterns [43].

In comparison with HSFO, ULSGO and ULSFO contain 97% less sulphur. For ULSGO, the PM emissions are reduced with approximately 60% [57]. As a result of the difference in lower heating values between distillate and residual fuels, all specific emissions are proportional reduced. Typical lower heating values of ULSGO and ULSFO are 42.7 MJ/kg and 40.0 MJ/kg [120], resulting in a reduction of 6% in specific emissions. However, in order to determine compliance with the regulations as specified in Chapter 2, the specific fuel consumption should be corrected to a reference lower heating value corresponding to the ISO 15550:2002 and ISO 3046-1:2002 standards. The use of a fuel with a higher Lower Heating Value is not accounted as CO_2 reduction method [66]. For ULSFO, the emission reduction is limited to the SO_x emissions only.

3.1.2. Very Low Sulphur Fuels

If the use of VLSGO or VLSFO will be the major compliance method for shipping in respect with the tightened global SO_x limits in 2020, this will be either because this is the fuel of choice for shipowners or because they use the wait-and-see approach regarding the 0.5% sulphur limit and only respond when their competitors are taking action. Till 2017, it was uncertain if there would be a delay of 5 years to the implementation date of the global 0.5% limit. After a study of CE Delft on the fuel oil availability in 2020, the proposal to delay the implementation date was rejected. CE Delft stated that the refinery sector has the capability to supply sufficient quantities of marine fuels with a sulphur content of 0.5% or less and with a sulphur content of 0.1% or less to meet the demand for these products, while also meeting the demand for non-marine fuels [43].

At this time, there is no existence of such fuels as VLSGO and VLSFO. It is likely to happen that before 2020, different types of bunkers with 0.5% sulphur will be produced. The difficulty will lie in the price and availability of these fuels. The experience of the development of the 0.1%S bunkers at the start of 2015 suggests that the market for these fuels will be fragmented, with several different specifications on offer [78].

Some crude oils are sweet enough to produce VLSFO directly from a refinery's crude distillation unit, which was not possible in case of ULSFO. In other cases, fuel oils may be desulphurized using hydrogen or other catalysts to produce a cleaner grade. Residues from a refinary's hydrocracker or vacuum distillation unit may also be used, either on its own or blended with fuel oils and middle distillates. Blended products in particular may not be reliable stable or may be incompatible with other fuels. This can lead to sludge forming at the bottom of the fuel tanks, risking blocked filters or even engine failure [78].

The emission reduction of VLSGO and VLSFO is in line with the emission reduction of ULSGO and ULSFO. In comparison with HSFO, VLSGO and VLSFO contain 86% less sulphur. PM reduction of VSLGO is with 60% equal to ULSGO [57]. No reductions on NO_x and CO_2 are attained.

3.1.3. Liquefied Natural Gas

The use of LNG as ship fuel has gained more attention in the past years. The use of LNG will reduce SO_x emissions to nothing and is thus compliant with the strictest sulphur limits [87]. Besides the elimination of SO_x emissions, due to a lower carbon content of LNG compared to conventional ship fuels enables up to 20% reduction of CO_2 emissions [55]. The typical reduction of NO_x emissions when changing from oil to gas is in the area 80-90% [117]. PM emissions can be reduced by 99% [87].

LNG propelled ships can either be equipped with a dual-fuel engine or a pure gas engine, both using the lean burn principle [158]. Applying the lean burn principle results in reduced peak temperatures and therefore reduces NO_x emissions [47]. Dual-fuel engines are able to run on LNG or distillate fuels. When using high pressure direct injection, LNG is injected at the end of compression and the engine operates according to the Diesel cycle. When using low pressure injection, LNG is injected at the start of compression and the engine operates according to the Otto cycle. In both cases, a small amount of distillate fuel is injected as pilot fuel for ignition [18]. When burning liquid fuels, the dual-fuel engine runs always according to the Diesel cycle. Two-stroke engines making use of high pressure injection system only reduce the NO_x emissions up to 40% [163]. This means that they fulfill only the Tier II requirements and therefore need to be combined with an EGR or SCR system when considering this engine for Tier III compliance [103]. All four-stroke engines available today are low pressure injection engines and operate according to the Otto cycle when burning LNG [18]. Low pressure injection engines are able to meet the Tier III requirements on its own and are able to reduce NO_x emissions up to 90% [117]. Pure gas engines need to be equipped with a spark plug and operate according to an Otto cycle. Only four-stroke pure gas engines are available at this moment. These engines are able to meet the Tier III limits on its own [142].

The advantage of high pressure direct injection engines is that no methane slip occurs as a result of combustion, because they operate according to the Diesel cycle [142]. Low pressure injection engines are able to meet the Tier III limits on its own but have a challenge on minimizing methane slip [142]. Methane slip that occurs across the entire supply chain remains a problem for all dual-fuel and gas engines [90]. Methane has a much higher greenhouse warming potential than CO_2 and is therefore a major concern when using LNG. The Kyoto protocol gives Methane a value that is 21 times the Global Warming Potential (GWP) of CO_2. This means that an unburned methane molecule has 21 times the GWP of one molecule of CO_2 [163]. Besides the significant emission reduction of LNG as a fuel, another advantage is the lack of potential compatibility issues, as consistent specification of the fuel should be available at all ports with LNG bunkering facilities [78].

Converting existing ships to LNG operation is possible, however conversions are expensive and technically challenging. LNG retrofit costs are typically an order of magnitude higher than scrubbers [1]. Other challenges include installing the fuel tank and containment systems and engine conversion [96]. Depending on the ship type, fuel tanks on existing ships may have financial consequences because the space needed for these tanks are cutting down on the amount of cargo a vessel can carry. The reason is the cylindrical size of the tanks and the low density of LNG [131].

Under normal circumstances, LNG will be cheaper than low sulphur bunkers. While the LNG bunkering infrastructure is currently limited to mainly European ports, it is expected that these facilities will be developed in the coming years. EU member states are even required to have at the end of 2025 a core network of LNG bunker points in seaports [87].

3.1.4. Biofuels

Biofuels are currently globally available, they can be produced from many abundant types of biomass, and they can be optimized to match the existing distribution channels and applications. There are many different kinds of biofuels including, but not limited to biodiesel, bio-ethanol, straight vegetable oil, dimethyl ether and bio-LNG [44]. In this thesis, the application will be limited to biodiesel and bio-LNG. Whichever form of biofuel is used, the application will be used as direct substitution for current conventional fossil fuels and compatible with existing infrastructure and engine systems. Technical problems, such as instability of on-board stored fuel, corrosion and bio-fouling are readily surmountable [111]. From a technical integration point of view, small percentage bio-diesel blends up to 20% with distillate fuels seems the most promising option for existing ships, due to best compatibility with current engines and supply chain [44]. Bio-LNG is still an upcoming technology.

The absolute CO_2 emissions from a ship burning only biofuels are equivalent compared to the use of fossil fuels. However, the CO_2 emissions of the entire life-cycle of the fuel with the production and transportation process involved is nearly nothing. Biofuels are considered CO_2 neutral. This means that the CO_2 in the biofuels has been absorbed from the air through growing biomass, and therefore when it is released through burning on a ship, the net emission is considered to be zero [44]. Biofuels are currently only used for blending up to 20% and therefore only influences the emissions proportional to the blend rates. Bio-diesel has two technical bottlenecks that are potentially problematic. The first bottleneck is that bio-diesel acts as a solvent and has a tendency to soften and degrade certain rubber and elastomar compounds which often are used in older engines. Therefore at higher blends, rubber hoses and seals may need to be replaced with synthetic, biodiesel resistant material [111]. The second bottleneck is that bio-diesel potentially removes deposits in the fuel system left by petroleum diesel, which could clog filters. Therefore, filters should be checked and cleaned regularly [111]. When distillate fuel is replaced by bio-diesel, the NO_x emission generally increases with about 10% as a result of a combination of the biofuels effect on ignition timing, ignition delay, adiabatic flame temperature, radiative heat loss and other combustion phenomena [82]. This increase is linear, so that the use of a 20% biodiesel blend results in an increase of about 2%. Reduction of PM is around 50% at complete replacement of bio-diesel. Bio-diesel does not contain any sulphur and therefore, the reduction in sulphur content is proportional with the blend rate [44].

Bio-LNG could be an alternative to LNG. Limited investigations regarding bio-LNG are currently going on. At this time, the scattered availability of bio-gas in general in Europe would be limiting the introduction of bio-LNG as long as no intra-European bio-gas certification scheme allows local bio-gas production facilities to introduce their bio-gas at central LNG terminals within Europe [44]. So, bio-LNG is not feasible in the near future but is seen as a alternative for LNG on the long term.

3.1.5. Fuel cells

Fuel cells have been receiving increased interest as alternative power supply for ships because fuel cells eliminate SO_x, PM, NO_x and CO_2 emissions when fuelled with hydrogen [146]. A fuel cell power pack consists of a fuel and gas processing system and a stack of fuel cells. Fuel cells produce energy from an electro-chemical process rather than combustion [129]. The process can be described similar to that of a battery, with electro-chemical reactions occurring at the interface between the anode or cathode and the electrolyte membrane, but in contradiction to the battery with continuous fuel and air supplies [146]. Fuel cells have no moving parts but require additional support plants such as pumps, fans and humidifiers. The reactants oxygen and gaseous hydrogen are combined in the fuel cell to produce water, releasing both electrical energy and some thermal energy in the process [129].

Hydrogen can be stored either as liquid or as high pressure gas [125]. Due to the low volumetric density of hydrogen, it is of great importance to have storage systems that are able to reduce the volume requirement of hydrogen by increasing the pressure or reducing the temperature. The high pressures required lead to prismatic tanks being used, which do not make such efficient use of internal space [125]. The volumetric density of compressed hydrogen at 350 bar is 23.3 kg/m^3. The volumetric density of liquid hydrogen is slightly more with 53 kg/m^3. These figures indicate that, even with volume reduction by increasing pressure or reducing temperature, the volume required remains a fraction of the volumetric density of residual fuels, which typically have a density of 1010 kg/m^3 [125].

The efficiency of a hydrogen and fuel cell combination could have a higher efficiency compared to the current Diesel engines [125]. However, Diesel engines significantly outperform fuel cells in terms of specific powers and power densities [129]. Fuel cells produce DC electrical output and are therefore only suitable for electric propulsion. Although hydrogen is easy to use, it would require a worldwide infrastructure to be developed for supply to ships.

3.1.6. Exhaust Gas Recirculation

Exhaust Gas Recirculation is a mature technology that already has been used in automotive engines for several decades [96]. This technology is a primary approach that reduces the NO_x emissions produced by modifying the combustion process. EGR involves recirculating a portion of the exhaust gases back into the combustion chamber and so lowering both the temperature and concentration of oxygen for combustion [158]. The EGR blower can adjust the amount of exhaust gas that is recirculated. EGR reduces the temperature peaks that produce maximum NO_x emissions during combustion [158]. At this moment, the application of EGR to achieve Tier III compliance is only available for two-stroke engines. For four-stroke engines, the EGR technology is under development but requires new engine technology. In fact, EGR on four-stroke engines is challenging because there is insufficient gas flow [130].

The exhaust gas can either be taken out of the exhaust stream before the turbine or after the turbine. When taking the exhaust gas before the turbine, the exhaust recirculates between the high pressure exhaust manifold and the high pressure inlet manifold as illustrated in Figure 3.1, therefore this system is called the high-pressure EGR system. When taking the exhaust gas after the turbine, the exhaust recirculates between the low pressure after the turbine and the low pressure before the compressor as illustrated in Figure 3.2, therefore this system is called the low-pressure EGR system. Both configurations are available on the market but investigations demonstrate that low-pressure EGR systems show lower initial and running costs but high-pressure EGR systems are able to reach higher reduction rates, as required for Tier III compliance [31].

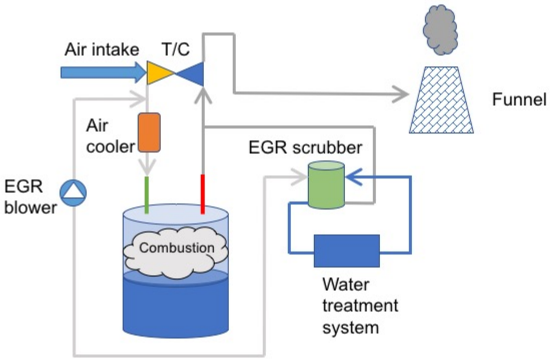


Figure 3.1: High-pressure EGR [31]

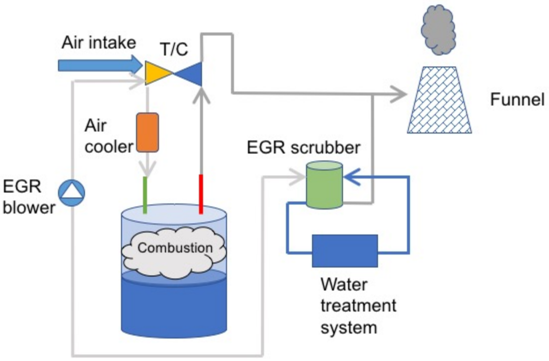


Figure 3.2: Low-pressure EGR [31]

EGR systems are able to achieve NO_x reductions up to 80% at a EGR rate of 40% [102]. There is however a specific fuel consumption (SFC) penalty when using EGR of up to 7% [152]. This drawback can be partly reduced by using a fuel optimized engine [158]. The removal of SO_2 has found to be above 95% and removal of PM is above 85% [57]. Because this only applies to the gas recirculated to the combustion chamber, the overall reduction in SO_2 and PM at the end of the exhaust line is found to be respectively 38% SO_2 and 34% PM at 40% recirculation.

3.1.7. Conclusion

Primary control methods seems to be effective in order to reduce emissions en meet the regulations because they tackle the pollution at the source. Especially SO_x and PM emission can almost or completely be eliminated by alternative fuels. NO_x emissions can be reduced by burning gaseous fuels or using EGR, which require a major conversion of the engine. CO_2 is the most difficult emission to tackle and needs, like NO_x, fundamental changes to the propulsion arrangement. The most promising and sustainable primary control method is the use of fuel cells in combination with hydrogen. However, undeniable challenges on this control method like storage and infrastructure causes this control method to be commercially unfeasible at this moment.

3.2. Secondary control methods

The secondary control methods that are considered in this section are in principle emission related. Wet or dry scrubbers are an alternative way to comply with the SO_x emission limits. In case of using a scrubber, the operator is not forced to use low sulphur bunkers and may still use HSFO. Both wet and dry scrubbing technologies are established and have been used in industries such as electricity generation for many years [96]. However, the only marine dry scrubber supplier has gone out of business and therefore only wet scrubbing is a possible solution in the marine industry at this moment [96]. Secondary techniques for NO_x reduction are very attractive in avoiding engine efficiency penalties, something what for example the primary control method EGR not can avoid. CO_2 emissions are mostly related to the efficiency of the ship and can be reduced by applying waste heat recovery as secondary control method. Waste heat recovery results also in an absolute reduction of SO_x, NO_x and PM emissions through a reduction in fuel consumption [101]. Although, in order to determine emission compliance, the specific fuel consumption should be corrected to a reference value and therefore the reduction in SO_x and NO_x emissions is not a valid reduction measure in order to achieve compliance on SO_x and NO_x regulations. The variety of other CO_2 reduction methods are non-engine related and will therefore not be discussed in this thesis. PM emissions are reduced by a combination of the use of cleaner fuel, scrubbers and improving engine performance [29].

3.2.1. Wet scrubbers

Wet scrubbing is a simple, robust and effective technique [96]. There are three main types of wet scrubbing:

- Open loop systems, which use seawater to treat the exhaust gas.
- Closed loop systems, which use fresh water with the addition of an alkaline chemical to treat the exhaust gas.
- Hybrid systems, which are able to operate in both open loop and closed loop modes.

An open loop system uses seawater for exhaust gas scrubbing as illustrated in Figure 3.3. The seawater is pumped from the sea through the scrubber. The natural chemical composition of seawater neutralizes the impact of SO_x in the scrubber water. Leaving the scrubber, water is discharged into sea without further treatment [104]. Wash water is not recirculated. The washwater flow rate in open loop systems requires approximately 45 m^3/MWh when a fuel with 2.7% sulphur content is used [95]. The alkalinity of the seawater needs to be sufficiently high for effective scrubbing. The open loop system is the cheapest solution in regards to installation and operating costs. However, an open loop system lacks flexibility when regulations prevent or limit the use of the system due to low alkalinity or restricted local discharge criteria [104].

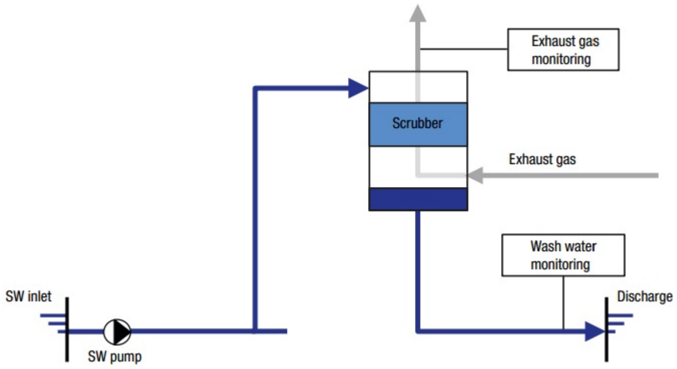


Figure 3.3: Open loop scrubber system [104]

A closed loop system uses fresh water that is chemically treated, usually by sodium hydroxide (NaOH) as the scrubbing media. This results in the removal of SO_x from the exhaust gas stream as sodium sulphate [95]. Rather than the once-through flow of an open loop scrubber, the washwater from a closed loop scrubber will be recirculated, as illustrated in Figure 3.4. The sulphate and PM from the combustion process accumulates in the scrubber water. Sulphate and PM must be removed continuously to avoid an increase in salinity and contamination of the system [104]. The contaminated water is bleeding off from the circulation tank and replaced by fresh water. Before discharging the bleed-off water, sludge is led to a sludge tank after a cleaning process performed in the water cleaning unit (WCU) . The closed loop system offers a high degree of flexibility as the use is not restricted by local regulations. However, the initial costs and operating costs are higher compared to the open loop system due to additional equipment and the use of chemicals. The flow rate in a closed loop system requires approximately 30 m^3/MWh and a discharge of 0.1 to 0.3 m^3/MWh [104]. The system is able to operate with zero discharge for limited time periods [96].

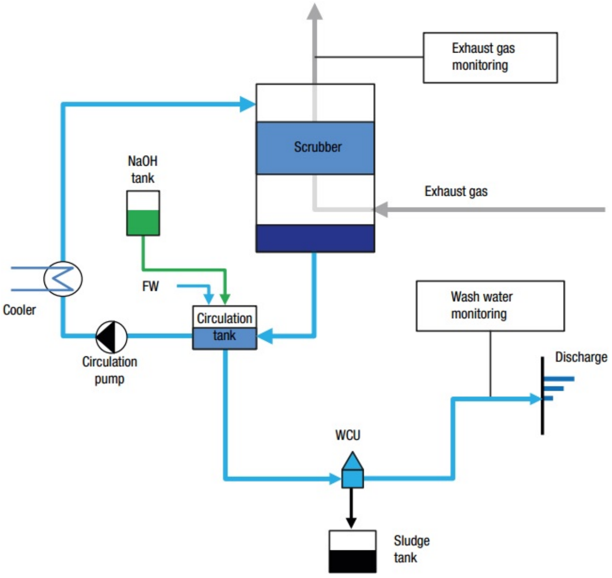


Figure 3.4: Closed loop scrubber system [104]

Hybrid scrubbers can operate in either open loop or closed loop modes, as illustrated in Figure 3.5. These scrubbers provide the flexibility to operate in closed loop mode where the water alkalinity is insufficient or where it is not allowed to discharge washwater, and in open loop mode at all other times [96]. The combination optimizes the chemical consumption and ensures that discharges do not affect sensitive areas with little water exchange [104]. The initial costs of the hybrid system are higher, due to the existence of components of both systems. However, the system offers the lowest operating costs as it can switch in the most economic mode.

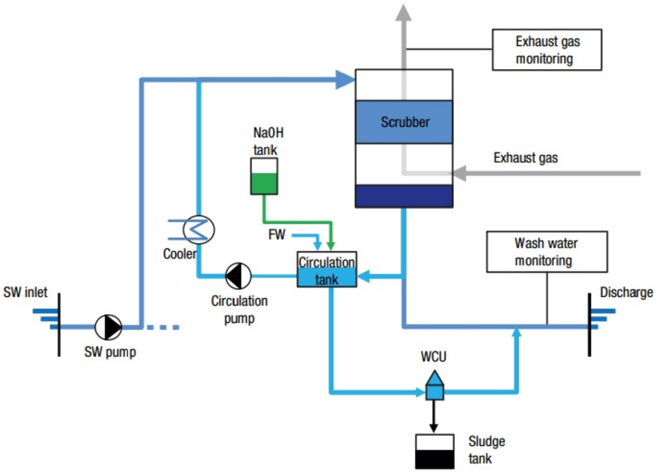


Figure 3.5: Hybrid loop scrubber system [104]

All types of scrubbers, either be an open loop, closed loop or hybrid scrubber, are able to remove up to 97% SO_x and 94% PM from HSFO [55] [57]. The CO_2 emissions from a vessel with a wet scrubber will be higher due to increased back pressure and power requirement of additional equipment. An acknowledged number for the increased power consumption of the scrubber is 2% [83]. As vessels with scrubbers are very unlikely to adopt a different fuel type in the future, these measures may slow down the non-fossil fuels in the future [24].

The principle advantage of scrubbers is that they allow to continue HSFO while remaining compliant with the strictest SO_x regulations. However, this comes at a cost because the investment needed to install the equipment can go up to $6 million per vessel [78], depending on the ship type and engine size. That capital will be saved in lower fuel bills over time. The speed of return on investment will be determined by the price differential between HSFO and low sulphur fuels. A highly unpredictable factor influencing the success of the scrubbers will be the availability and price of the HSFO. HSFO is currently widely available but if the major compliance option for the 0.5% sulphur limit will be the change over to low sulphur fuels, the demand of HSFO will drop dramatically. One scenario as a result of the fall in demand is that the price increases due to the balance in supply and demand. Additional supply chain costs may be thought of as barges transporting HSFO cannot thereafter load low sulphur bunkers but have to be cleaned first. In the worst case scenario, the availability of HSFO will be affected, especially in small ports. The opposite scenario is that the price of HSFO will drop because there will be suddenly a large oversupply of HSFO, as the fuel will remain a residual product of the distillate process.

3.2.2. Selective Catalytic Reduction

Selective Catalytic Reduction (SCR) is considered the most promising way to meet the most strict Tier III standard with a NO_x abatement capability of up to 95% [7]. Furthermore, SCR has proven to be popular for equipment manufacturers because it allows NO_x control with only a minor net fuel efficiency penalty, because manufacturers can tune their engines for maximum fuel efficiency and use SCR to clean up the resulting NO_x [7]. The SCR concept involves injecting an urea-water solution into the exhaust gas stream in combination with a catalyst unit in the exhaust channel [31]. The process requires a certain minimum engine exhaust gas temperature, therefore the use of SCR under low engine load conditions is challenging [31]. Despite this systems may allow for optimizing parameters resulting in a minor reduction of fuel consumption, the CO_2 emissions may increase up to 1% as a result of the urea consumption [93]. SO_x and PM emissions are not affected by a SCR system. Figure 3.6 illustrates a high-pressure SCR system that is used for two-stroke engines where the SCR system is typically placed upstream of the turbocharger to provide the catalyst with a sufficiently high exhaust temperature. Figure 3.7 illustrates a low-pressure SCR system that is used for four-stroke engines where the exhaust temperature is sufficiently high to allow efficient catalyst operation after the turbocharger [96].

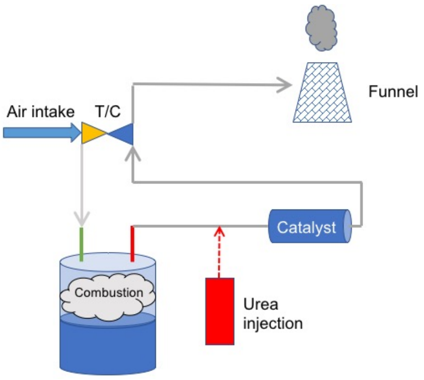


Figure 3.6: High-pressure SCR [31]

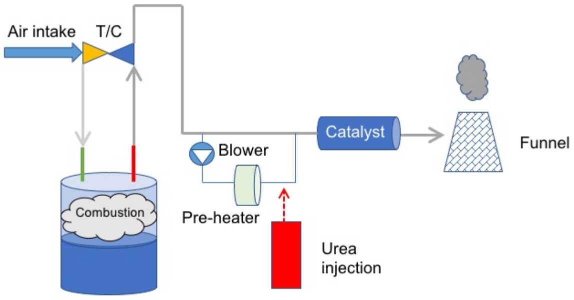


Figure 3.7: Low-pressure SCR [31]

SRC systems can also be used with high-sulphur fuels in combination with a scrubber, if properly designed and maintained [31]. If the SCR system is installed after the scrubber, then the exhaust needs to be heated in order to obtain the required reduction in NO_x emissions from the SCR system. If the SCR system is placed before the scrubber, then there is no need for any modifications [107].

No limitations in SCR applications can be considered for continuously running four-stroke engines coupled to a controllable-pitch propeller. However, there are still some challenges with two-stroke engines, which are always directly coupled to a fixed-pitch propeller and must be able to run at extremely low loads. In such operational modes, the SCR unit must be switched off [31]. Instationary transitional engine loads do not fall under Regulation 13 of MARPOL Annex VI [73]. However, defeat devices and irrational control strategies undermining this intention are strictly prohibited [31].

3.2.3. Waste Heat Recovery Systems

Despite their high brake efficiency, Diesel engines waste large amount of heat to the environment, mainly by the exhaust gas [8]. The exhaust gas energy is an attractive waste heat source because of the heat flow and temperature. It is possible to generate an electrical output up to 11% of the main engine power by utilizing this exhaust gas energy in a waste heat recovery system comprising both steam and power turbines, and combined with utilizing scavenge air energy for exhaust boiler feed-water heating [101]. Typical methods of heat recovery in marine applications are:

- STG - Steam Turbine Generator unit
- PTG - Power Turbine Generator unit
- ST-PT: Steam Turbine-Power Turbine generator unit

STG applications for Waste Heat Recovery Systems (WHRS) include direct heat recovery from waste heat boilers. In this system, part of the exhaust gas bypasses the turbochargers in order to increase the exhaust gas temperature before the boiler without using a power turbine. This will increase the obtainable steam production power for the exhaust gas boiler. By installing a steam turbine, the obtainable steam production from the exhaust boiler system can be used for electric power production [101]. A PTG-WHRS is the simplest and cheapest system and consists of an exhaust gas turbine installed in the exhaust gas bypass, and a generator that converts power from the power turbine to electricity onboard the ship. The power turbine is driven by a part of the exhaust gas flow which bypasses the turbochargers. The power turbine produces extra output power for electric power production, which depends on the bypassed exhaust gas flow amount [101]. With a combined ST-PT WHRS as illustrated in Figure 3.8, both the STG-WHRS and the PTG-WHRS are combined together to form a combined system [105].

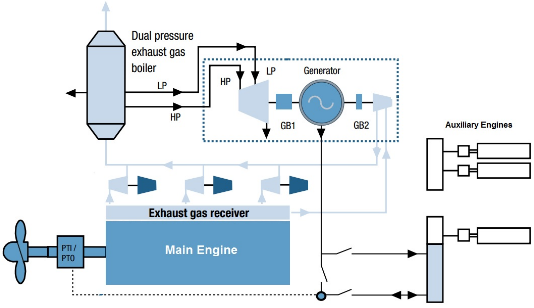


Figure 3.8: ST-PT generator unit [101]

The absolute emissions and fuel consumption of the engine are not changed when using a WHRS. Because extra power can be generated from the exhaust stream, the auxiliary engines are able reduce their power proportional to the power delivered by the WHRS and the emissions of the auxiliary engines will decrease accordingly. Based on the fuel saving, the total efficiency of the ship is increased and therefore improving the EEDI and emission profile of the ship.

The application of WHRS opens the possibility of fuel consumption reductions in the range of 4-11%, depending on the selected WHRS solution, engine power level, operational profile, etc. A WHRS gives absolute emission reductions for all emissions due to reduced fuel consumption as a result of the WHRS application [105]. The drawback of WHRS is that the systems can only be applied to engines with a large power output and thus a sufficient enough energy flow of waste heat.

3.2.4. Conclusion

Secondary control methods reduce the emissions of a ship after they are created in the engine. These methods are mostly related to one emission. It can be concluded that each single method can be very effective in order to reduce the corresponding emission. So is wet scrubber effective for reducing SO_x emission, SCR for reducing NO_x emissions and WHRS for reducing CO_2 emissions. The combination of all those systems might be impossible because each particular system takes a large amount of space in the exhaust line behind the turbocharger. Therefore, secondary control method seems to be a good intermediate solution to meet one single emission regulation. For long term solutions, the emissions need to be clearly eliminated at their source.

3.3. Comparison

The emission reduction potentials of SO_x, NO_x, CO_2 and PM are given in Figures 3.9, 3.10, 3.11 and 3.12. The reduction potentials are given in comparison with the conventional used HSFO. From the bar plots of the different emissions can be concluded that CO_2 has the greatest challenge in reduction. Only hydrogen is able to eliminate CO_2, where for the other emissions alternative abatement options are available.

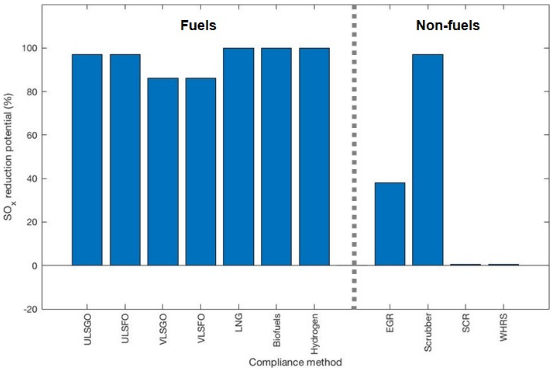


Figure 3.9: SO_x reduction potentials

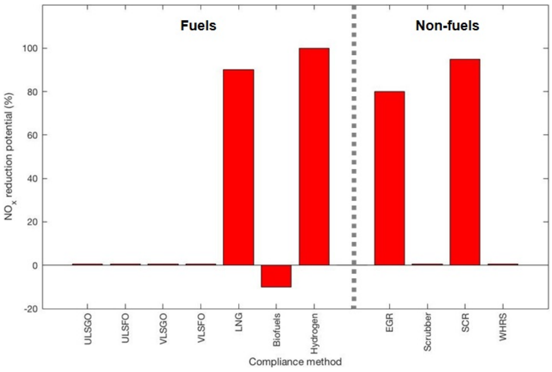


Figure 3.10: NO_x reduction potentials

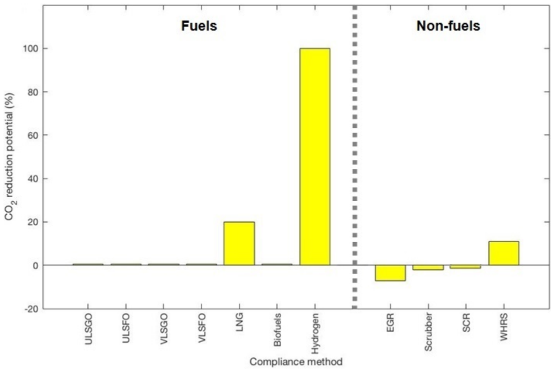


Figure 3.11: CO_2 reduction potentials

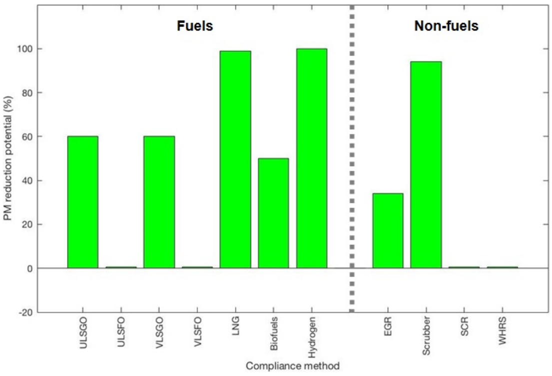


Figure 3.12: PM reduction potentials

The majority of all ships have installed conventional Diesel engines used for propulsion and power generation. Conventional Diesel engines are designed to burn residual fuels but the sharpened SO_x regulation inside the SECAs enforced in 2015 shows a shift to distillate fuels. Before 2015, there was no use to burn the relative expensive distillate fuels. As alternative to the fossil fuels, distillate fuels can be blended or replaced by bio-diesel. All fuels compatible with the different engines and fuel cells are given in Table 3.1.

Table 3.1: Fuel compatibility with engines and fuel cells

	Distillate Fuels	***Residual Fuels***	***LNG***	***Biofuels***	***Hydrogen***
Diesel Engine	C	C	N	C	N
Dual Fuel Engine	C	C	C	C	N
Gas Engine	N	N	C	C	N
Fuel Cells	N	N	N	N	C

^{C} Compatible
^{N} Non-compatible

The dual fuel engine is a modified Diesel engine and offers a fuel flexibility that looks increasingly appealing in an uncertain fuel marketplace. The dual fuel engines can be fuelled by distillate fuels, residual fuels and LNG. Both the distillate fuels and LNG can be blended or replaced by biofuels. The single gas engines operate only on LNG or bio-LNG. The engine operates fundamentally different and uses the Otto cycle instead of the Diesel cycle. The last technique that can be used for power generation is the use of fuel cells with hydrogen. This technique is still in its infancy but is likely to be a viable option for the future.

Paragraph 3.1 and 3.2 introduced a portfolio of available abatement techniques, other than the change of fuel. However, not every abatement technique is compatible with all engines and fuel cells. Table 3.2 gives an overview of the possible application of abatement techniques on the engines and fuel cells considered. The considered abatement techniques are all compatible with the Diesel engine. For gas and dual-fuel engines, only SCR is compatible. For other techniques, it is either not technically feasible to apply the technique on gas and dual-fuel engines. As the use of hydrogen in combination with a fuel cell has zero emissions, there is no need to apply any additional abatement techniques.

Table 3.2: Compatibility of engines and fuel cells with abatement techniques

	EGR	***Scrubber***	***SCR***	***WHRS***
Diesel Engine	C	C	C	C
Dual Fuel Engine	N	N	C	N
Gas Engine	N	N	C	N
Fuel Cells	N	N	N	N

^{C} Compatible
^{N} Non-compatible

As not every abatement technique complies with every energy converter, also the combination of abatement techniques has its restrictions. In Table 3.3, the compatibility of different abatement techniques is given. EGR and SCR are usually not combined because EGR reduces the exhaust gas temperature and SCR requires a minimum exhaust gas temperature to ensure effective catilization. Besides that, there is no reason to invest in two different abatement systems while SCR is also able to achieve Tier III compliance on its own, as EGR is as well for two-stroke engines. WHRS are not combined with EGR and scrubbers, as those techniques reduce the exhaust gas temperature significantly. This makes the advantage of WHRS very limited.

Table 3.3: Compatibility of different abatement techniques

	EGR	***Scrubber***	***SCR***	***WHRS***
EGR	-	C	N	N
Scrubber	C	-	C	N
SCR	N	C	-	C
WHRS	N	N	C	-

^{C} Compatible
^{N} Non-compatible

3.4. Conclusion

As emission limits become more stringent, compliance becomes more challenging and costly. For each emission type, there are a number of ways to comply. This chapter gave insight in the compliance method that are appropriate, technical possible and sustainable for each of the regulated emissions. The compliance methods that are indicated as feasible can be used in the model to determine the most cost effective compliance method in the long term. Each compliance method faces its own different technical and operational challenges. The only method that eliminate all emission completely is the use of fuel cells in combination with hydrogen and the application of electric propulsion. However, the challenges on this abatement option regarding storage and bunkering infrastructure are significant. A transition between the emission free fuel cells and the current used Diesel engines can be the use of LNG, either on a retrofitted dual fuel engine or a single gas engine. LNG eliminates not only the SO_x emissions, as LNG contains no sulphur, but it reduces the other emissions significantly.

The first upcoming emission regulation is the global sulphur limit that will be enforced in 2020. The use of low sulphur fuels seems to be the major compliance option for existing ships because it requires minor investment costs. However, the operational expenses may increase over time but strongly depend on the price development of different fuel types. The only available technology that provide substantial reduction on SO_x emissions, other than the change of fuel, is a scrubber and allows the use of HSFO, which might become cheaper after this sulphur limit is enforced. The use of LNG and the blending of bio-diesels are also considered as compliance option.

The regulation of NO_x emissions is only applicable to ships build after the enforcement date of the regulation and therefore it does not require ships build before the enforcement date to retrofit in order to comply with this regulation. However, ships build in 2016 or later are facing the challenging requirements set by Tier III to reduce the NO_x emissions by 80%. Quite a number of NO_x reduction methods are available but only SCR and EGR on two stroke engines are sufficient to meet these requirements if using oil based fuels. Other options are the use of LNG and the use of fuel cells in combination with hydrogen. Both of them requiring a large amount of space for fuel storage. Also improvement of the worldwide bunker facilities on these fuels is needed to make this option feasible for worldwide sailing ships.

The timing of CO_2 measures that will come into effect in the near future is still uncertain, therefore there should be kept a sharp eye on the effects of the abatement options on CO_2 emissions to be able to anticipate when those regulations will be enforced. For example, the installation of scrubbers lead to an increase in CO_2 emissions of 2% due to the increased back-pressure and pump power. It is highly undesired, but not unimaginable that this increase in CO_2 emissions will counteract when new CO_2 limits are enforced. Secondary effects with respect to possible future emission regulations should be taken into account when selecting abatement techniques.

4

Problem approach

One typical characteristic related to shipping investments is the considerable amount of capital that is needed [80]. The rapid technological developments, increasing regulatory pressure and possible cashflow problems mean that ship owners have a need for a relative short time horizon for return on investments. The first section of this chapter explains two different approaches of how an investment analysis can be carried out. In the next section, two mathematical approaches that can be used to set up the decision-support method for the selection of emission control methods will be discussed and reviewed for the case of Seatrade. Reference is made to studies done in the past on the selection of emission control methods. In the third section, the most common financial structures in shipping will be discussed to identify the corresponding efficiency and risks. Based on the selected investment approach and mathematical approach, a conceptual framework is made that can be used to set up the optimization model. As last section in this chapter, a methodology for the decision-support process will be described. This methodology describes the outline of the tool that will be developed.

4.1. Investment analysis

An investment analysis is a financial analysis conducted for investment purposes [76]. Either a top-down or bottom-up investment approach can be used. A top-down approach with respect to emission compliance looks first for macro economic opportunities and restrictions before working down to the best compliance option. On the other hand, a bottom-up approach looks at the benefits of a single compliance option on a single ship before the influences of the whole shipping cycles are considered.

The top-down approach mainly looks into historical data of the market cycle [76]. Shipping, in that respect, is an industry characterized as being highly cyclical, volatile, capital intensive and highly leveraged [51]. The combination of volatile earnings and low returns distinguishes shipping from other investments [143]. In a recessed shipping market, the interest and capital repayments might constitute a problem for companies as they may not have sufficient cashflows to meet their obligations. This might be enhanced when the fleet is operating in the spot market rather than in the time-charter market [51].

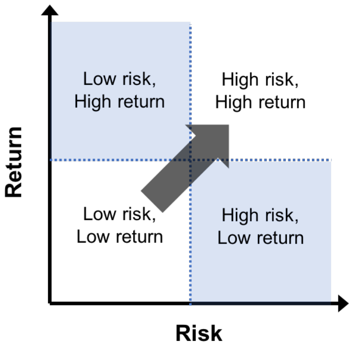


Figure 4.1: Pricing of conventional investments

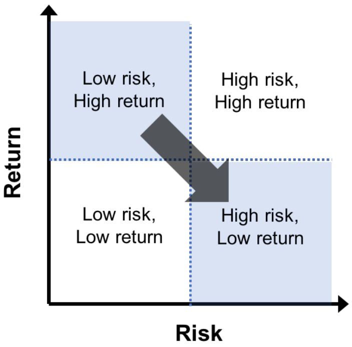


Figure 4.2: Pricing of shipping investments

Figure 4.1 shows the relationship between risk and return of a general investment. For conventional investments, more volatile investments pay higher returns and will be priced along the arrow [143]. Although, shipping investors have different risk preferences, which are indicated by the arrow in Figure 4.2. In this case, returns are negatively correlated with volatility [143]. Shipping entrepreneurs are attracted to the high risk and low-return option by the opportunities offered by the volatility of the shipping cycles [143]. The volatility of the shipping cycles allow ship owners to make fabulous profits on the purchase and sale of ships, when trading the assets on the right time in the shipping cycle [143]. In case of considering emission compliance in a booming shipping market, an installed abatement technique may add more value to the ship that the value of the investment. The reason is that the prices for installing or retrofitting an abatement technique will rise, because investors have the financial resources to invest, rather than having a wait-and-see approach, as is seen in a down-turned market. Also, waiting times at the shipyards will be longer, which causes the added value of the investment also to rise.

The bottom-up approach looks more to the future potential, in contradiction to the top-down approach. The bottom-up approach uses investment indicators such as the Net Present Value (NPV) and the Internal Rate of Return (IRR). The NPV is calculated by discounting the future cash flows using a discount rate reflecting the required return and is often used to compare investments in different projects [80]. The IRR is the discount rate that returns an NPV of zero and can be used to get insight in the efficiency of one investment [80].

4.2. Mathematical approach

Ship owners usually base their decisions on a pure financial deterministic criterion to compare costs and benefits in a bottom-up approach [132] [77]. A deterministic approach does not simulate uncertainties, such as technical complexity of the installation, fuel prices, availability of fuels, etc. When using this mathematical approach, uncertainties can become insightful by running the model multiple times with varying uncertain parameters. The most common used deterministic approach in shipping is based on the NPV criterion. The NPV criterion is described as the time value of money, that dictates that time affects the value of cash flows. Cash flows of nominal equal value over a time series result in different effective value cash flows that make future cash flows less valuable over time [126]. The NPV is given by equation 4.1 where t represents the time of the cash flow, C_t the net cash flow at time t and r the discount rate. The discount rate is the return that could be earned per unit of time on an investment with similar risk.

$$NPV = \sum_{t \in T} \frac{C_t}{(1+r)^t} \tag{4.1}$$

When applying the NPV to the selection of emission control methods, only comparing costs is possible because quantifying environmental benefits can not be done easily. Besides that, without applying emission control methods and thus not complying with the regulations, the ship is not allowed to sail anymore.

Schinas and Stefanakos [132] argue in their research that such a simplified approach as the NPV criteria might not be sufficient for solving a complex problem and that a more sophisticated approach is required. A more sophisticated approach is the use of a stochastic method, which is able to include criteria that can not be expressed in pure cost terms. The research of Kana et al. [79] suggests the use of a Markov Decision Process (MDP) framework for analyzing the use of LNG as fuel in the face of uncertainty. MDPs are designed to model and solve dynamic stochastic sequential decision-making problems. They are state-based representations of systems that handle uncertainties, can differentiate actions, and can handle non-stationary developments [79]. The classic MDP is defined as a tuple $< S, A, T, R >$ in which S is a finite set of states, A a finite set of actions, T a transition probability function and R a reward function [124]. The outcome identifies an optimal policy that maximizes the cumulative, long term utility. The optimal policy can be obtained via equation 4.2, known as the Bellman equation, where U is the expected utility, γ the discount factor and s' the state in the next epoch in time.

$$U(s) = R(s) + \gamma \, max \sum_{s'} T(s,a,s') \, U(s') \tag{4.2}$$

The outcomes of a deterministic method compared to a stochastic method can vary significantly [164]. For example, in a deterministic approach the availability of the fuel is assumed as sufficient or not, while in an stochastic method the supply risks can be quantified or randomly determined. A thorough example to indicate the differences of both methods is the flipping coin example. You take a coin of 1 euro, you may keep the money if you get heads and lose the money if tails are on any toss. The outcome of the deterministic method will be either 0 or 1, depending on the assumptions that are made. The outcome or expected value of the stochastic method will be 0.5 euro, which is the long-run average value of repetitions of the experiment. The difference is, the output of a deterministic method is fully determined by the parameter values and assumptions that are made while a stochastic method possesses some inherent randomness and may have a different outcome with the same set of parameters.

For the case of Seatrade, the deterministic approach with the use of NPV criteria is found most appropriate [79] [132] [164]. The key drivers for using a pure financial criteria are, despite the limitations, simplicity and the outcome of numbers that can be directly reflected to a real case. Ship owners do not add more value to results from a stochastic method because ship owners want to have those numbers as results rather than expected values [132]. The results of the deterministic approach are an accurate reflection of a real case, where the stochastic approach is an average of all possible cases with the probabilities taken into account. Uncertainties such as variation of the fuel prices and availability of the fuels can not be neglected and take a significant share in the outcome of the analysis. The way to tackle this is to run the model multiple times with varying the highly sensitive parameters in each run. In this way, the sensitivity and influences of these parameters will become insightful in a qualitative manner.

In addition to the NPV method, the payback periods will be calculated for those emission compliance methods that result in a reduction of costs after doing the investment, which is for example the case for scrubbers and dual-fuel engines. NO_x reduction measures result usually not in a reduction of costs and therefore will not be payed back in a reasonable time frame. The payback periods can be calculated in two different ways, with taking into account the time value of money either as nominal or discounted value. The nominal payback period is widely used and is the first period (n) which satisfies the following condition:

$$\sum_{t=0}^{n} C_{1,t} \leq \sum_{t=0}^{n} C_{2,t} \tag{4.3}$$

For which C_1 is the cashflow of the considered project and C_2 is the cashflow of the project used as reference. In words, the nominal payback period is the first period for which the accumulated cashflow of the considered project is below the accumulated cashflow of the reference project.

The discounted payback period is less popular but has added values compared to the NPV method and the nominal payback period. The NPV method ensures profitability but not liquidity, the nominal payback period ensures liquidity but not profitability. The discounted payback period is the only criterion which covers both the liquidity and profitability of a project [14]. The discounted payback period is the period during which the cumulative net present value of a project's cash flow drops below the cash flow of the benchmark project. Mathematically, the discounted payback period is the first period (n) which satisfies the following condition:

$$\sum_{t=0}^{n} \frac{C_{1,t}}{(1+r)^t} \leq \sum_{t=0}^{n} \frac{C_{2,t}}{(1+r)^t} \tag{4.4}$$

For which C_1 is the cashflow of the considered project and C_2 is the cashflow of the project used as reference. The discount rate is defined as r. In words, the discounted payback period is the first period for which the accumulated discounted cashflow of the considered project is below the accumulated discounted cashflow of the reference project. A project is acceptable if the discounted payback period is less than its economic life or some predetermined period.

The discounted payback period can be interpreted as a period beyond which a project generates economic profit whereas the nominal payback period gives a period beyond which a project generates accounting profit [14]. The discounted payback period will always be greater than the nominal payback period. The discounted payback period has one limitation that is shares with the nominal payback period, that it ignores the cash flows beyond the computed payback period. Given that, the combination of the discounted payback period and the NPV results give substantiated criteria to base a decision on. There should be kept in mind that the cash flows used in the NPV method should be different from the cash flows used in the calculation of the payback periods. The cash flows used in the NPV method include financing. For the calculation of the payback periods, financing methods, other than equity, are not considered [6].

4.3. Financial decisions

A financial decision relates to the capital sources the company prefers to finance its investment projects with [144]. A rough distinction of capital sources can be made between equity financing and external funding. Equity financing is a self-sustained or internal funding and is free of debt. External funding is a debt and interest need to be paid to the lender [80]. A more extensive explanation on finance sources is given in appendix A.

The nature of finance sources for investments in shipping is currently somewhat changing. Back in the days, highly leveraged financial structures were justified by having the cash flow secured before the actual order was placed [5]. Today, in the aftermath of the financial crisis, cash flow is uncertain and banks are more reluctant to give out loans and ship owners are required to have a bigger share of equity or use different sources of finance [5]. A shift has been observed from commercial bank loans to bond issues and private placements [49]. Figure 4.3 gives an overview of today's most common capital sources.

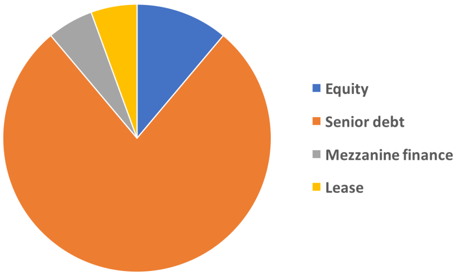


Figure 4.3: Major sources of shipping finance [49]

The capital structure of each investment consists of the relative proportion of equity, debt and other outstanding securities [144]. Next, different structures and the influence of those structures on the return that may be expected will be discussed. The financial structures are explained based on an example described by Van den Burg et al. [150]. The example has the following characteristics:

Vessel price	24.0 M$
Senior debt	65% swapped for 7 years, priced at 5.5%
Employment	Bareboat charter at 8400 $/day
Sale price after 7 years	Unknown
Book value in year 7	15.0 M$

In the discussion of the different structures, the Internal Rate of Return (IRR) is used as a measure for capital budgeting. The IRR is often used to get insight in the efficiency of the investment. In the example, only one investment is considered with multiple outcomes and the IRR is preferred [150]. The IRR is calculated by solving the inequality given in equation 4.5.

$$\sum_{i=0}^{n} \frac{CashFlow(i)}{(1+IRR)^{i}} = 0 \tag{4.5}$$

The example gives a number of commonly used financing structures. However, many more options and combinations exist as there are many different options for repayment schemes, interest rates, boundaries and equity kickers. The basic structure of finance is plain vanilla and only uses senior debt. Using this financing structure, a higher profit can be made on the investment compared to the case where only equity is used [150]. The reason is that the leverage is increased. Leverage is the ratio of the debt of a company to the equity of a company and amplifies the profits or losses [128]. Too much leverage, however, can lead to the risk of default and bankruptcy [119]. Senior debt is secured by a first-priority mortgage registered over the vessel. This means that the ship can be seized by the creditors and sold in case of default [143].

Figure 4.4 shows two cases. The first case represents the case where the ship described in the example is entirely financed by equity. In the second case, senior debt for 65% of the investment is added with a linear repayment scheme and a duration of 7 years. The sale price of the vessel after 7 years in uncertain and is shown as a variable. The figure shows clearly that the senior debt will amplify the profit in all cases, because the yearly return is more than 5.5% of the bank loan. However, if the vessel will be sold below 10 M$, the leverage will start to work in the opposite direction, reducing the profits of the owner.

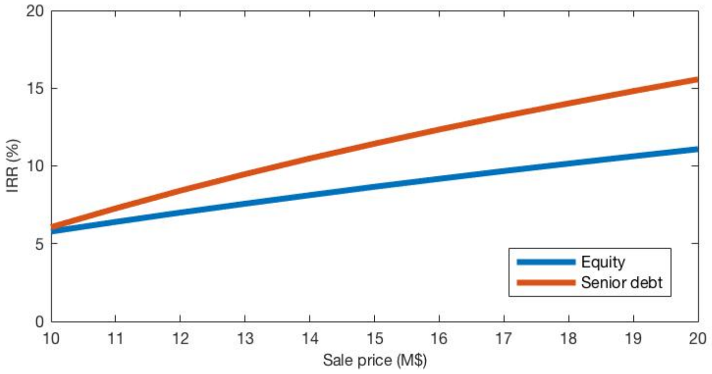


Figure 4.4: IRR by senior debt

Mezzanine can be used as a form of additional financing on top of the senior debt. It provides more leverage, but comes at higher costs. The interest rate for mezzanine debt will be higher than the interest rate for senior debt, as there is no mortgage applicable to mezzanine finance [150]. Figure 4.5 shows the difference as a result of taking an layer of mezzanine finance over the senior debt. The situation as described above where only senior debt is used, is shown as reference. The case where a mezzanine layer is taken shows a steeper slope, meaning that the profits and losses will be more amplified. Mezzanine finance is more expensive and therefore, the turning point whether or not this financial system is more profitable comes at a higher revenue. The situation described in this example has assumed a bullet payment at the end of the period and an yearly interest rate of 10%. It can be concluded that the risk taken in this situation is higher than only using senior debt. The third case shown in Figure 4.5 shows the same combination of senior and mezzanine debt, but now with an equity kicker of 25% on the sales profits included. This means that if the actual sale price is higher than the book value of 15 M$, the mezzanine provider will receive 25% of this overvalue. This however only effects the sales price, the cash flows will be the same with and without equity kicker [150].

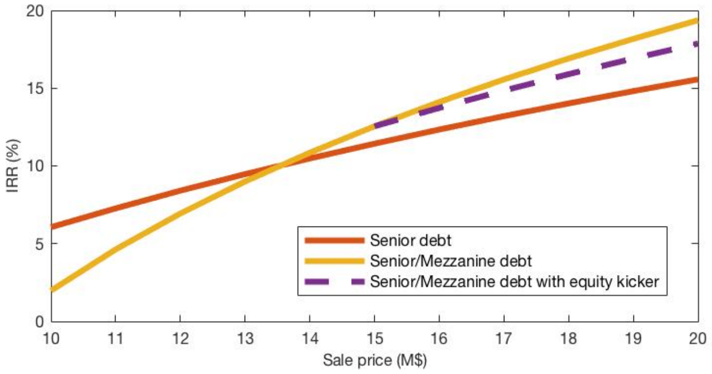


Figure 4.5: IRR by senior and mezzanine debt

Seller's credit is a financial system where a seller grants a buyer the right to defer payment of part of the purchase price [62]. Basically, the delay is a loan on the vessel and draws interest. The ship owner pays this amount back at the end of the confirmed period, similar to a bullet payment. In a clause can be agreed that the buyer only needs to pay if the value of the vessel is above a certain value at the end of the agreed period. Seller's credit is usually issued by the ship yard in rough economic times to boost the orderbook of the ship yard [150]. More recently, seller's credit has been also offered by subcontractors or equipment suppliers to buyers in order to facilitate financing requirements [62]. The seller's credit of a new or secondhand vessel can be secured by a second-priority mortgage, after the first-priority mortgage of the bank. For equipment suppliers, the registration of a charge over the equipment as a means of securing the seller's credit is often not a viable option. As an alternative, seller's credit granted by an equipment supplier may be secured by a parent company or other form of guarantee [62].

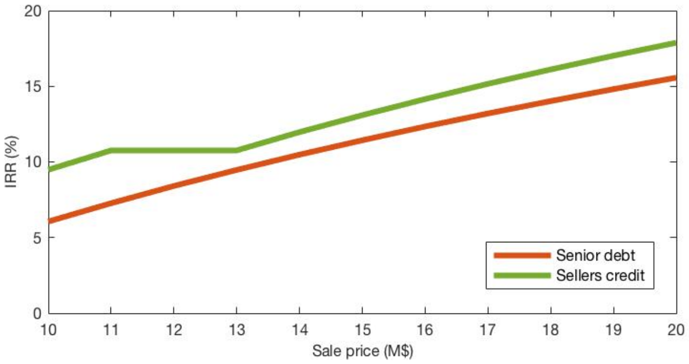


Figure 4.6: IRR by senior debt and seller's credit

The graph shown in Figure 4.6 gives the effect of the seller's credit on the IRR. In the example, a seller's credit of 2 M$ is included with a interest rate of 4%. The interest is usually lower than the interest for senior debt, which is another benefit for the ship owner. The loan is subordinated to equity with a sales price of 13 M$. This means that if the price is less than 13 M$, the ship owner can deduct the difference from the payment of 2 M$ to the yard. The risk is reduced and the return is increased. The IRR is higher on the entire range of the sale prices.

4.4. Conceptual framework

The conceptual framework of the model consists of a clear goal, different aspects, criteria and alternatives. The goal of the research is clearly defined in Chapter 1. The aspects are in fact key parameters that are optimized in order to reach this goal. Three groups of criteria are set. The financial criteria are resulting from the aspects in order to minimize costs. The technical criteria are set by the technical limitations related to the existing configuration and design of the ship. The regulatory criteria are resulting from the IMO and authorities in the form of regulations. The alternatives that are available to reach the goal of the model are captured in Chapter 3 and are combinations of an engine type, fuel types and abatement techniques. The conceptual model framework is given in Figure 4.7.

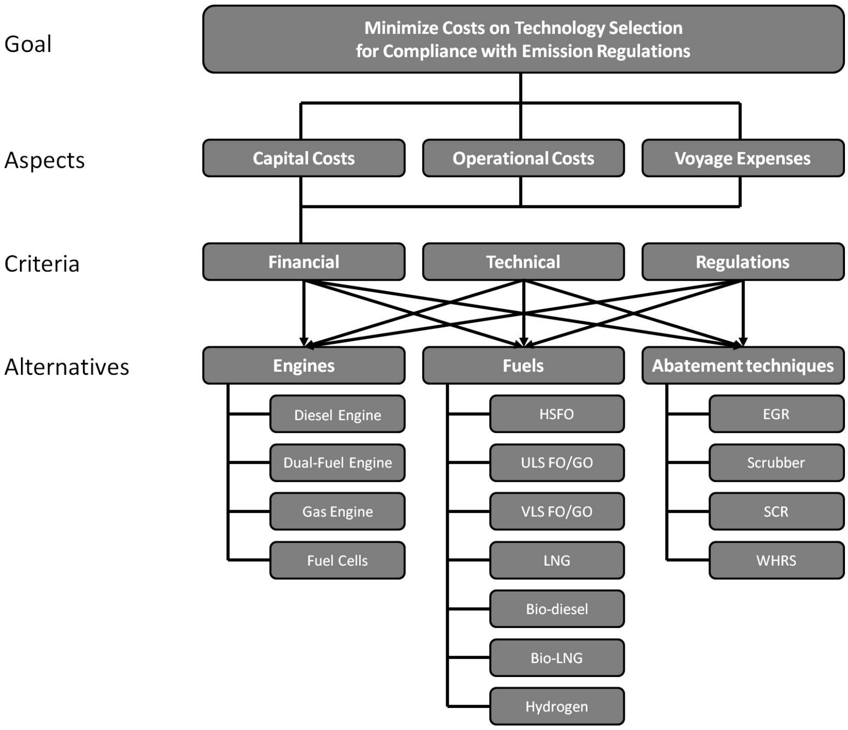


Figure 4.7: Conceptual model framework

The goal of the decision-support model is to minimize costs of the technology selection for compliance with emission regulations. The costs are split into three aspects, each contributing to the goal. Each alternative has different influences on the aspects. For example, the installation of a scrubber requires a significant amount of capital but reduces the voyage expenses significantly. On the other hand, the use of ULSGO has almost no influence on the capital costs but the voyage costs may increase significantly.

The criteria are set from a regulatory, technical and financial point of view. The financial criteria are used to rank the feasible options based on cost aspects. The regulatory criteria are set by authorities, mainly by the IMO. The technical criteria are restrictions from a technical perspective. The regulatory and technical criteria are constraints to the optimization model and are limiting the number of feasible alternatives. With respect to the technical constraints, newbuilding ships have more flexibility for choosing the optimal combination of alternative engines, fuels and abatement techniques because the design of the ship can be adjusted to the chosen alternatives and the payback time is maximum. For ships that are going to be retrofitted, the lay-out of the ships is matching to the initial state of the ship. Space issues with respect to the installation of new equipment or other engines may be a big constraint in retrofitting cases [19]. In the case of Seatrade, the initial situation of ships that needs to be retrofitted is for most ships a two-stroke Diesel engine running on HSFO in global areas and ULSGO in SECAs. In principle, no abatement techniques are installed.

Lots of alternatives are possible, as 4 engine types, 9 different fuels and 4 abatement techniques are considered. Multiplication of those alternative components leads to 5184 unique options in each time step (4 x 9 x 9 x 16). The fuels used inside and outside SECAs may differ and need therefore taken into account twice. The installation of no abatement technique or combinations of more than one abatement techniques are also possible. However, not every combination of those alternatives are compatible with each other, which should be clearly defined in the constraints of the model. This will reduce the number of possible alternatives significantly. For example, the installation of all 4 abatement techniques is counted as an alternative, but will be eliminated by the technical constraints.

4.5. Decision-support methodology

The decision-support methodology that will be used in this study assists as a tool for important decision making in the life-cycle analysis of a ship's propulsion machinery. The resulting life-cycle strategy minimizes the costs of the emission reduction measures. The methodology consists of 6 different steps as presented in Figure 4.8.

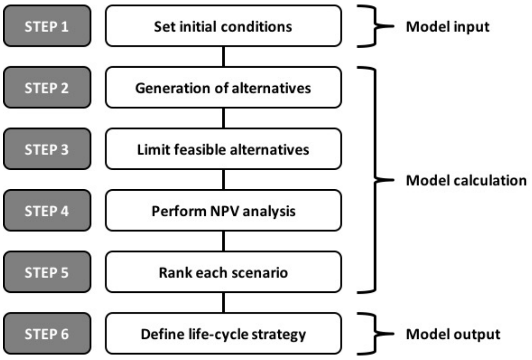


Figure 4.8: Methodology for the decision-support process

First, the initial conditions have to be set in step 1. The initial conditions includes parameters that are different for each case. Among other things, the initial conditions include costs of equipment, fuel prices, voyage parameters, sailing area, ship parameters, etc. As second step, all combinations of alternatives will be generated. In this process, no criteria are taken into account. The alternatives include all possible combinations of the engine type, fuel types and abatement techniques in each time step, which are mentioned in section 4.4. The list of alternatives is huge long and a selection of those alternatives need to be made before the NPV analysis can be performed. In step 3, the feasible alternatives are filtered out by using financial and regulatory criteria, because there is no need to perform calculations on alternative options that are technically not feasible or restricted by the regulations. All feasible alternatives will be subject to the NPV analysis in step 4. The results of the NPV analysis will be ranked on cost aspects in step 5. Based on this ranking, a suggested life-cycle emission reduction strategy will be given in step 6.

The input of the optimization model consists of parameters that are set in step 1 of the decision-support methodology. In steps 2 till 5, a list of alternative options is created, selected, calculated and ranked. These steps include the model calculations, that will be described in Chapter 5. Step 6 of the decision-support process will be the output of the model and defines the life-cycle emission reduction strategy of the ship.

4.6. Conclusion

The bottom-up approach is found to be most appropriate when considering the future potential of investments [76]. The counter option is the top-down approach, which can hardily be applied to the investment analysis on emission compliance methods because this approach mainly relies on historical data. Historical data is scarcely available because similar projects does not exist in sufficient quantities. Besides that, the suitable compliance method is very dependent on the existing shape and configuration of the ship, especially for retrofit. Therefore, it is easier to eliminate particular compliance options, that are not suitable to the considered ship, in an early stage. The selection of the appropriate investment approach is important for the next step, where the mathematical approach is selected. For a top-down approach, a more statistical analysis should be carried out. However, in this case where using a bottom-up approach, financial indicators will be used. The financial indicators can both be used in a deterministic and stochastic mathematical approach. The difference is how there will be dealt with uncertainties. For a project considering an investment in the future, not a few uncertainties are involved in the result of the analysis. The deterministic approach is selected, where uncertainties become insightful by a qualitative manner. The confidence of the user and decision maker has been decisive in this point. The outcome of a deterministic approach reflects a possible scenario in reality, while a stochastic approach results in an expected value, which is less tangible. As a result, ship owners acting as decision makers prefer the deterministic approach [132] [77].

The chosen capital structure for an investment is critical for the risk and profitability of the project. A highly leveraged capital structure increases the potential magnitude of return but also increases the financing costs. Depending on the certainty of the cash flow as a result of the investment, an optimal leverage ratio can be found by weighing the cost of debt against its benefits [5]. Financing methods for newbuilding ships are widely available on the capital market. The tenor of debt is usually 10 till 15 years [143]. For retrofit projects, it is not easy to find investors willing to put capital in an old ship. Those projects might need be financed by 100% equity. For expensive retrofit equipment, it is going to mean that retrofit will be not an option, as shipping companies usually have a low equity-to-debt ratio and are not able to meet the financial obligations by equity only [150].

In the conceptual framework, the structure of the decision-support tool is being visualized. Because it is difficult to convert the environmental benefits of emission reduction measures into money, only the cost aspects will be used in the NPV analysis. Technical and regulatory criteria will be used to eliminate infeasible alternatives. Financial criteria, defined by the common used cost items on a ship's balance sheet, will be used to rank the feasible alternatives. The outcome of the decision-support process will be used as a strategy on the selection of emission control methods for the entire life-cycle of the ship. The conceptual framework and the decision-support methodology together give a substantiated foundation of the optimization model.

5

Optimization model

This chapter will cover the mathematical description of the optimization model. The model consists of an objective function and constraints. The objective is to minimize the total life-cycle costs. The constraints define conditions that solutions to the objective function must satisfy. In the definition of the objective function, distinction is made between the different financial classifications a shipping company is working with. The method that will be introduced in this chapter will be used to perform the case studies. The optimization models from Balland et al. [10] [11] are used as a starting position. The first model from Balland et al. gives an optimization model for retrofitting controls for regulation compliance and is proposed in 2014 [10]. This model is later extended by Balland et al. [11] in order to address the emission regulation compliance of a vessel in the design phase. One of the motivations for taking the emission regulation compliance into consideration in the design phase is the fact that some controls can only be implemented when the vessel is being built as they affecting, among others, the shape of the hull [11]. Besides that, some controls may have lower installation costs if implemented as part of the initial design rather than being retrofitted. In the design phase, the emission control selection is mutually dependent with the choice of the machinery system, while for retrofitting, the emission control selection is mainly dependent on the choice of fuel or installation of additional reduction measures [11]. The machinery system needs to be chosen in order to meet the requirements as stated by the ship owner, while the retrofitting emission controls have been decided through the operational phase of the vessel life-cycle. By combining these decisions, the life-cycle strategy may become more cost effective. The models from Balland et al. [10] [11] are combined and adjusted to the case of Seatrade.

5.1. Notations

The notations are introduced before the mathematical formulation of the objective function and the corresponding constraints are presented and explained. In Table 5.1, the sets used in the model are presented.

Table 5.1: Model sets

Sets	
A	Abatement techniques
A_e	Abatement techniques compatible with engine e
A_{EEDI}	Abatement techniques considered by the EEDI
C_{IGF}	Crew subject to IGF code
E	Engine types
F	Fuel types
F_e	Fuel types compatible with engine e
I_{EEDI}	Engines installed
K	Emission types
O	Operational situations
T	Time periods

In Table 5.2, the indices used in the model are presented.

Table 5.2: Model indices

Indices	
a	Abatement technique
e	Engine type
$seca$	Operational situation: SECA
f	Fuel type
c	Ship's crew
c/f	CO_2-to-Fuel
gl	Operational situation: global
i	Installed engine
k	Emission type
mcr	Condition at MCR
o	Operational situation
ref	Reference value
$serv$	Service value
t	Time period

In Table 5.3, the parameters used in the model are presented.

Table 5.3: Model parameters

Parameters		
ACE	*($)*	Abatement technique conversion engineering costs
ACT	*(d)*	Abatement technique conversion time
AIE	*($)*	Abatement technique installation engineering costs
ATC	*($)*	Abatement technique conversion costs
ATI	*($)*	Abatement technique installation costs
ATP	*($)*	Abatement technique purchase costs
B	*(g/Tnm)*	Required EEDI
BT	*(T)*	Bruto tonnage
BTC	*($)*	Bruto tonnage port charge
$CAPEX$	*($)*	Capital expenses
CAT	*(-)*	Additional crew for abatement technique
CB	*($)*	Costs of consumables
CBU	*($/MWh)*	Costs of consumables per energy unit
CC	*($)*	Crewing costs
CCF	*(-)*	Carbon content in the fuel
CD	*(d)*	Course duration
CE	*(MWh)*	Energy consumption
CEN	*($)*	CAPEX for newbuilding projects
CER	*($)*	CAPEX for retrofit projects
CF	*($)*	Course fee
COF	*($)*	Costs of finance
COI	*($)*	Costs of interest
COR	*($)*	Costs of repayments
COP	*($)*	Costs of payments
CP	*($/T)*	Carbon price
CT	*($)*	Carbon tax
CW	*($/day)*	Crew wages
DD	*($/d)*	Dry-dock day-rate
DDD	*(d)*	Dry-dock days
DR	*($/d)*	Day-rate of the ship

Parameters (continuation)

DWT	*(T)*	Deadweight
EC	*($)*	Engine conversion costs
ECE	*($)*	Engine conversion engineering costs
ECP	*($)*	Engine conversion purchase costs
ECT	*(d)*	Engine conversion time
EI	*($)*	Engine installation costs
EIE	*($)*	Engine installation engineering costs
EIP	*($)*	Engine installation purchase costs
EO	*(kW)*	Engine output
ESI	*(-)*	Environmental Ship Index
$ESI\ CO_2$	*(-)*	ESI CO_2 sub points
$ESI\ NO_x$	*(-)*	ESI NO_x sub points
$ESI\ SO_x$	*(-)*	ESI SO_x sub points
FC	*(T/y)*	Fuel consumption
FE	*($)*	Fuel expenses
FP	*($/T)*	Fuel price
G	*(%)*	Emission reduction goal
IC	*($)*	Insurance costs
IR	*(-)*	Insurance rate
L	*(y)*	Lifetime
LC	*(TEU/cbft)*	Loss of capacity due to installation of new equipment
LHV	*(MJ/kg)*	Lower heating value
LR	*($)*	Loss of revenue
LVN	*(g/kWh)*	Limit value NO_x
M	*(-)*	Large numbers
MC	*($)*	Maintenance costs
MCR	*(kW)*	Maximum Continuous Rating
MCU	*($/MWh)*	Maintenance costs per energy unit
OEA	*($)*	OPEX related to the abatement technique
OEE	*($)*	OPEX related to the engine
OEK	*($)*	OPEX related to the fuel
OHA	*(d)*	Off-hire time as a result of installation of new abatement techniques
OHE	*(d)*	Off-hire time as a result of engine conversion
$OPEX$	*($)*	Operational expenses
OPS	*(-)*	On-shore power supply installation ESI sub points
OT	*(h)*	Operation time
PC	*($)*	Discount on port charges
PCF	*(-)*	Power correction factor
Q	*(-)*	Conversion factor
r	*(-)*	Discount rate
R	*(%)*	Reduction potential
RDT	*(d)*	Regular dry-dock time
RVN	*(g/kWh)*	Rated value NO_x
SD	*($)*	Sludge disposal costs
SDC	*($/T)*	Sludge disposal costs per unit
SFC	*(g/kWh)*	Specific fuel consumption
SP	*(-)*	Sludge production rate
SPU	*(T / MWh)*	Sludge production per energy unit
TC	*(TEU/cbft)*	Total capacity of the ship
v	*(kn)*	Ship speed
VE	*($)*	Voyage expenses
x	*(%)*	Relative sulphur reduction of high sulphur fuels
y	*(%)*	Relative sulphur reduction of medium sulphur fuels
z	*(%)*	Relative sulphur reduction of low sulphur fuels

In Table 5.4, the binary variables used in the model are presented.

Table 5.4: Model variables

Binary variables	
$\alpha_{t,e}$	1 if engine e will be installed in time period t, 0 otherwise
$\beta_{t,a}$	1 if abatement technique a will be installed in time period t, 0 otherwise
$\gamma_{t,e}$	1 if engine e is used in time period t, 0 otherwise
$\delta_{t,a}$	1 if abatement technique a is used in time period t, 0 otherwise
$\epsilon_{t,o,f}$	1 if fuel type f is used in operational situation s in time period t, 0 otherwise
fr	1 if fuel is reported regularly for ESI purposes, 0 otherwise

5.2. Objective function

The objective function is desired to minimize the net present costs related to or influenced by the emission abatement techniques and methods. Costs are divided into the three classifications: Capital Expenses, Operational Expenses and Voyage Expenses. Capital Expenses (CAPEX) depend on the way a ship has been financed and include the interest and repayment of the ship and major retrofittings. Operational Expenses (OPEX) constitute the expenses involved in the day to day running of the ship including manning costs, stores, lubricants, insurance, repairs and maintenance. Voyage Expenses are variable costs associated with a specific voyage and include items such as fuel and port charges. All three categories are on its own way influenced by emission abatement techniques.

The objective function as given in equation 5.1 minimizes the total net present costs of installing and running the equipment used to control emissions over the entire lifetime of the ship. Each operating year of the lifetime of the ship is defined in set T. The parameters in the objective function are expressed in \$/y and variable over time.

$$min \sum_{t \in T} \frac{(\,CAPEX_t \,+\, OPEX_t \,+\, VE_t\,)}{(1+r)^t} \tag{5.1}$$

5.2.1. Capital Expenses

The CAPEX depend on the way a ship or a retrofitting project has been financed. These expenses are divided into the finance costs, capital expenses related to newbuilding and capital expenses related to retrofitting.

$$CAPEX_t \,=\, COF_t \,+\, CEN_t \,+\, CER_t \tag{5.2}$$

Financing

The CAPEX that will be calculated in this chapter are related to significant amounts of money. It rarely happens that a shipping company is able to finance such projects, especially newbuildings, only with equity. Projects can be financed in various ways, as is described in Chapter 4 and Appendix A. The use of all finance methods comes with additional costs. Those additional costs consist of the costs of the initial payment, which will be negative, the costs of repayments and the costs of interest. The accumulation of the initial payments and all repayments during the lifetime of the ship will equal 0. The interest costs are in fact the additional costs as a result of opting for finance methods other than equity.

$$COF_t \,=\, COP_t \,+\, COR_t \,+\, COI_t \tag{5.3}$$

Payment of the loan will be accounted for in the year before the investment project will become operational. For example, an investment is made for the installation of a scrubber. If the project will be completed at the beginning of 2020, the payment of the loan is accounted in 2019, the first repayment will be done in 2020. The specified periods of payment and repayment are important for the calculation of the NPV. Repayment can be taken into account by either a balloon repayment at the end of the period or a yearly repayment. If balloon repayment is contracted, the full amount of the invested value will be repayed at the end of the period. If yearly repayment is contracted, an equal share of the invested value will be repayed each year. Interest will be paid yearly over the outstanding loan. Meaning that for balloon repayments, the outstanding loan and thus the interest will be constant through the years. For yearly repayment, the interest will decrease proportional with the outstanding loan.

Newbuilding

The CAPEX related to newbuilding include the capital needed for the engines and additional abatement techniques. In this model, CAPEX that are not related to emission controls are not taken into account because they are equal for all situations independent of the selected emission controls. The binary variables in the equation indicate whether or not an engine or abatement technique is installed.

$$CEN_t = \sum_{e \in E} \Big(EI_e \cdot \alpha_{t,e} \Big) + \sum_{a \in A} \Big(ATI_a \cdot \beta_{t,a} \Big) \tag{5.4}$$

Installation of engines and abatement techniques for new-building is only possible at $t = 0$. This will be defined in Section 5.3 using constraints to the binary variables. Therefore, the engine installation costs are not variable through time and only dependent on the engine type. The CAPEX is split into engineering costs and purchase cost of the equipment.

$$EI_e = EIE_e + EIP_e \tag{5.5}$$

$$ATI_a = AIE_a + ATP_a \tag{5.6}$$

Retrofit

The CAPEX related to retrofitting include the capital needed for the retrofit projects. The binary variables in the equation indicate whether or not an engine or abatement technique is installed in a particular year.

$$CER_t = \sum_{e \in E} \Big(\big(EC_{t,e} + OHE_{t,e} \big) \cdot \alpha_{t,e} \Big) + \sum_{a \in A} \Big(\big(ATC_{t,a} + OHA_{t,a} \big) \cdot \beta_{t,a} \Big) \tag{5.7}$$

In contradiction to engine installation costs, the engine conversion costs are variable trough time, as these costs depend on if regular dry docking is planned in the corresponding year. As is done for newbuilding, the purchase costs and the engineering costs are included. In case of retrofitting, the engine purchase costs may also be significant less then when installing a new one, as in some cases the engine does not have to be entirely replaced. The price of installing additional abatement techniques may differ significantly for retrofitting in comparison to newbuilding due to space restrictions for retrofitting.

$$EC_{t,e} = ECE + ECP_e + DD \cdot \big(ECT_e - RDT_t \big) \tag{5.8}$$

$$ATC_{t,a} = ACE + ATP_a + DD \cdot \big(ACT_e - RDT_t \big) \tag{5.9}$$

The loss of revenue as a result of the off-hire of the ship is a result from the off-hire days multiplied by the day-rate of the ship. Dry dock costs are not included in this cost category but are included in the costs for conversion. If the retrofit is done during regular dry dock intervals and these intervals does not need to be extended, the off-hire costs are nil. This off-hire costs are a function of time as the scheduled dry docking is only once per 5 years.

$$OHE_{t,e} = DR \cdot \big(ECT_e - RDT_t \big) \tag{5.10}$$

$$OHA_{t,a} = DR \cdot \big(ACT_a - RDT_t \big) \tag{5.11}$$

5.2.2. Operational Expenses

The OPEX include the expenses involved in the day to day running of the ship. These costs are divided into operational expenses related to engines, fuels and abatement techniques.

$$OPEX_t = OEE_t + OEK_t + OEA_t \tag{5.12}$$

Engines

The OPEX related to engines include the costs related to maintenance, crewing and insurance costs. Maintenance costs are different for all type of engines and are difficult to estimate. Crewing costs can make a difference when additional courses are required for operating the equipment or when specially qualified personnel is required. This is especially the case for ships operating on LNG. Insurance costs may be higher for ships that have a different value as a result of the abatement techniques onboard.

$$OEE_t = \sum_{e \in E} \Big(MC_{t,e} + CC_e + IC_e \Big) \cdot \gamma_{t,e} \tag{5.13}$$

Maintenance costs are calculated as a function of the energy consumption of the engine. The energy consumption is expressed in MWh. This approach to account for maintenance costs is already used in previous researches by the Danish Maritime Authority [25] and the Interactive Knowledge Platform for Maritime Transport and Logistics [81].

$$MC_{t,e} = MCU_e \cdot CE_t \tag{5.14}$$

Handling low-flashpoint fuels on ships has become part of the maritime training standards since 2017. As described in Chapter 2, the required courses depend on the duties and responsibilities that the different crew members are accounted for. The additional crewing costs as a result of those additional courses are calculated by adding up the course fees with the labor costs for the time that the crew member is following the courses. The costs will be divided by 5 years to get the average yearly costs, as the certificates have a validity of 5 years. The number of crew that have to take the courses is usually multiplied by 2 because one part of the crew is on leave and one part of the crew is on board. This is not taken into account in the equation but should be taken into account in the variables that define the number of crew members.

$$CC_e = \frac{1}{5} \cdot \sum_{c \in C_{IGF}} \left(CF + CW_c \cdot CD \right) \tag{5.15}$$

The insurance costs in general are proportional to the value of the ship. In this case, the insurance costs for a specific engine are defined by the purchase value of the engine times the insurance rate that is applicable. The insurance rate is assumed to be constant through time.

$$IC_e = ECP_e \cdot IR \tag{5.16}$$

Fuels

The OPEX related to engines include the costs as a result of sludge disposal and consumables. The amount of sludge that need to be disposed is fuel dependent. Consumables related to the fuel is mainly the use of lubrication oil. For different fuels, the lubrication oil type needs to be changed. This might result in different costs.

$$OEK_t = \sum_{o \in O} \sum_{f \in F} \left(SD_{t,o,f} + CB_{t,o,f} \right) \cdot \epsilon_{t,o,f} \tag{5.17}$$

The amount of sludge that is created during settling and purification of the fuel does strongly depend on the fuel type. Heavy residual fuels are subject to many cleaning processes onboard and give away the highest amount of sludge. In comparison, gases such as LNG and hydrogen have no sludge disposal at all. The costs related to sludge disposal is a function of a percentage of the fuel consumption multiplied by the disposal costs per tonne of sludge.

$$SD_{t,o,f} = SDC \cdot SP_f \cdot FC_{t,o,f} \tag{5.18}$$

The consumable costs related to a specific fuel are taken very general. The costs are calculated as a function of the consumable costs per tonne of fuel and the total fuel consumption.

$$CB_{t,o,f} = CBU_f \cdot FC_{t,o,f} \tag{5.19}$$

Abatement techniques

The OPEX related to abatement techniques include the costs related to sludge disposal, maintenance costs, additional costs for insurances, consumable costs and crewing costs.

$$OEA_t = \sum_{a \in A} \left(SD_{t,a} + MC_{t,a} + IC_a + CB_{t,a} + CC_a \right) \cdot \delta_{t,a} \tag{5.20}$$

Sludge disposal for abatement techniques is mainly a result of the chemical remnant of a closed loop and hybrid scrubber. The costs are calculated as a function of the sludge price, sludge production and yearly energy consumption.

$$SD_{t,a} = SDC \cdot SPU_a \cdot CE_t \tag{5.21}$$

Maintenance costs are involved in all kind of abatement techniques but may vary in quantity. The maintenance costs related to abatement techniques are expressed as a function of the costs per energy unit times the yearly energy consumption.

$$MC_{t,a} = MCU_a \cdot CE_t \tag{5.22}$$

Insurance costs may be higher for ships having expensive equipment on board. Extra costs for insurances may also vary with the type of technology used. The value of the installation in combination with the possibility that something happens with the installation is decisive for the insurance costs. Insurance costs are calculated by the purchase value of the abatement technique times the insurance rate.

$$IC_a = ATP_a \cdot IR \tag{5.23}$$

Consumables includes scrubbing media and catalysts. Those yearly costs are a function of the costs per energy unit multiplied by the yearly energy consumption.

$$CB_{t,a} = CBU_a \cdot CE_t \tag{5.24}$$

Crewing costs for abatement techniques relate to the policy of the company. There do not exist any regulations on additional training courses in order to be able to operate abatement techniques. However, it might be necessary in a particular case to place one additional crew member onboard to operate the technique and ensure a safe operation.

$$CC_a = 365 \cdot CW_c \cdot CAT_a \tag{5.25}$$

5.2.3. Voyage Expenses

Voyage Expenses include all costs related to a specific voyage. The most significant component of the voyage expenses are the fuel costs. The port charges may also affected by the emission controls that are used. The space that is required for an engine, additional emission control or appendages may lead to a loss of cargo space. The result of this is loss of revenue during every single voyage. Lastly, a carbon tax will be included in the model. Such a tax does not exist yet but may be implemented in the future.

$$VE_t = FE_t + PC_t + LR_t + CT_t \tag{5.26}$$

Fuel expenses

The fuel expenses of one fuel type are defined as the annual fuel consumption multiplied by the projection of the fuel price of the corresponding year. To obtain the total fuel expenses of a ship, the sum needs to be taken of the fuel expenses of all fuel types.

$$FE_t = \sum_{f \in F} FC_f \cdot FP_{f,t} \tag{5.27}$$

The annual fuel consumption can be divided into three operational situations: fuel consumption for sailing outside a SECA, for sailing inside a SECA and during port stays. The operational situations are defined in set O. It is possible to use different fuels inside and outside a SECA, it is also possible to use the same fuels inside or outside a SECA if the fuel meets the requirements in both areas. The fuel used in ports depends on whether the port is located inside a SECA or not. The annual fuel consumption of each type of fuel is calculated by summing up the consumption figures of the respective fuel types in the respective operational situations. Those consumption figures are obtained by multiplying the SFC by the time yearly operated in that operational situation and the engine output in that operational situation. The binary variable ϵ is used to indicate which fuel is used in each operational situation and in each year.

$$FC_{t,f} = \sum_{e \in E} \sum_{o \in O} SFC_{e,o} \cdot OT_{e,o} \cdot EO_{e,o} \cdot \epsilon_{t,o,f} \tag{5.28}$$

The SFC is a variable parameter as function of the engine load. Besides that, the SFC curves for Diesel engines, dual fuel engines, gas engines and fuel cells are significantly different. The relation between the deviation in SFC and engine load for different engines expressed in g/kWh are given in Figure 5.1. The deviation given in the SFC curves is with respect to the SFC value at MCR. The value that is used in the calculations is an interpolated value between the known points on the curves.

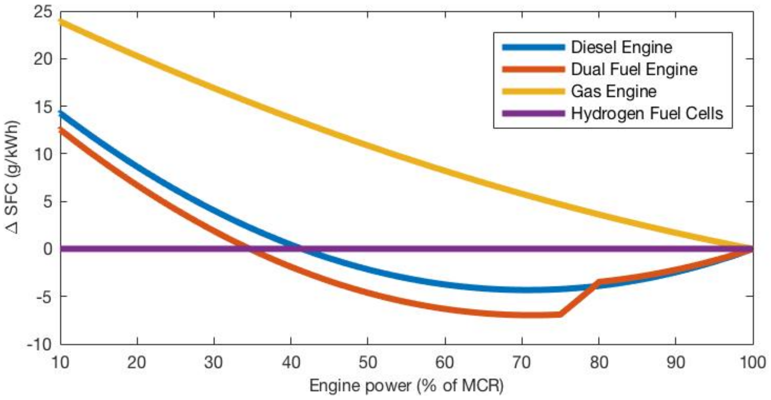


Figure 5.1: SFC curves for different types of engines

The SFC curves for Diesel engines and dual-fuel engines given by the manufacturer are usually related to fuel oil with a Lower Heating Value (LHV) of 42.7 MJ/kg as reference value [103]. The given SFC values needs to be corrected to the correct SFC by the ratio of the reference LHV and the LHV of the fuel in use. For gas engines, the SFC curve is usually given in terms of MMBTU/h but is in Figure 5.1 already converted to g/kWh [114]. The SFC of a fuel cell does, unlike combustion-based engines, not vary much with the load factor [147].

$$SFC_{e,o,f} = SFC_{ref,e,o} \cdot \frac{LHV_{ref}}{LHV_f} \tag{5.29}$$

The ngine output is calculated as a function of the MCR of the engine, the ratio of the service speed of the ship and the speed of the ship at MCR and the power correction factor. The power correction factor accounts for the efficiency increase or decrease as a result of the abatement techniques. For example, if a WHRS is installed and lead to a efficiency increase of 10%, the PCF will be 0.90.

$$EO = \left(\frac{v_{serv}}{v_{mcr}}\right)^3 \cdot MCR \cdot PCF_a \tag{5.30}$$

Port charges

The discount on port charges as a result of the use of emission abatement techniques or cleaner fuels will be calculated as a product of the Environmental Ship Index (ESI). Not all ports may give an discount on the port charges in this way, but at least this method will give a fair and substantiated approximation. At least 50 ports are connected to this way of giving discounts [162]. The discount that is taken into account in the calculation will be based on the current discount in the Port of Rotterdam and can be adjusted accordingly [121]. The discount is 10% of the bruto tonnage port charge.

$$PC_t = \begin{cases} (1 - 0.1) \cdot BT \cdot BTC_t & \text{if } ESI_t \geq ESI_{req} \\ BT \cdot BTC_t & \text{otherwise} \end{cases} \tag{5.31}$$

The ESI is an international benchmark for emissions from seagoing vessels and is intended to be used by ports to reward ships when they participate in the ESI. For example in the port of Rotterdam, sustainable ships receive a discount on port charges when they score high on the ESI [121]. Vessels that perform better than the legal norm will be rewarded a 10% discount on the gross tonnage part of the port dues. The discount is doubled when vessels also have low NO$_x$ emissions. The required ESI to qualify for the discount may vary per year. The ESI is built up from different parts for NOx, SOx and CO2. Additionally, a bonus is awarded for the presence of an On-shore Power Supply Installation (OPS). The ESI score ranges from 0 for a ship that meets the environmental performance regulations in force to 100 for a ship that emits no NO$_x$ and SO$_x$ and reports or monitors data to establish its energy efficiency [162].

$$ESI_t = \frac{1}{3}\left(2 \cdot ESI\ NO_{x\,t} + ESI\ SO_{x\,t} + ESI\ CO_{2\,t} + OPS\right) \tag{5.32}$$

The NO$_x$ sub points are calculated with the NO$_x$ emissions levels based on the rated power per engine.

$$ESI\ NO_{x\,t} = \frac{100}{\sum_{i \in I_{EEDI}} MCR_i} \cdot \sum_{i \in I_{EEDI}} \frac{(LVN_i - RVN_i) \cdot MCR_i}{LVN_i} \tag{5.33}$$

The SO$_x$ sub points reflect the reduction in sulphur content of the fuels below the limit values. In equation 5.34, x represents the relative reduction of the average sulphur content of fuels with a high sulphur content (between 0.5% and 3.5%), y represents the relative reduction of the average sulphur content of fuels with a medium sulphur content (between 0.1% and 0.5%) and z represents the relative reduction of the average sulphur content of fuels with a low sulphur content (up to 0.1%).

$$ESI\ SO_{x\,t} = x \cdot 30 + y \cdot 35 + z \cdot 35 \tag{5.34}$$

The $ESI\ CO_2$ is a measure for the efficiency of a vessel and is calculated based on comparison between a base line period of 3 years in which the totals of fuel consumption and distance sailed in that period are reported. Reporting during the 3 year period adds 5 points to the ESI score and any efficiency increase in % in the reporting period is added to the ESI score as points, with a maximum of 15 points. In this (simplified) case, the efficiency increase is calculated as the sum of the CO$_2$ reduction potentials of the different emission control methods. Only retrofit measures are beneficial for the ESI CO$_2$, because for newbuilding ships the baseline has to be determined in the first three years a ship is operating.

$$ESI\ CO_{2\,t} = 5 \cdot fr + \sum_{f \in F} R_f \cdot \epsilon_{t,o,f} + \sum_{a \in A} R_a \cdot \delta_{t,a} \tag{5.35}$$

Loss of revenue

Loss of revenue as a result of a reduction in cargo capacity depend very much on the abatement option and ship type that is considered. There is assumed that no volume reduction in the cargo holds is obtained due to the installation of abatement techniques. The loss of revenue as a result of installing abatement techniques can be best defined as a function of the mass that is added to the ship, which reduces the cargo capacity, expressed in mass. For engines, there is assumed that there will not be large mass differences between the engines itself. But for using gases as fuel, additional volumes are required for storage. Therefore for engines, the loss of revenue can be best defined as a function of volume that reduces the cargo capacity.

The fleet of Seatrade consists of both containerships and reeferships. The approach between those two ship types need also be tailor made. For containerships, the cargo capacity is usually expressed in Twenty Foot Equivalent Units (TEU) . The days that the loss of revenue is applied will be only the sailing days, the days that the ship is at sea. For reeferships, the cargo capacity is usually expressed in cubic foot (cbft). The days that the loss of revenue is applied will be similar to the on-hire periods used in a time charter, being all days minus the days that the ship will be in drydock. Table 5.5 gives an overview of the units that will be used in order to calculate the loss of revenue.

Table 5.5: Loss of revenue units

	Engine	***Abatement Technique***
Containership	volume, TEU	mass, TEU
Reefership	volume, cbft	mass, cbft

For a containership, the loss of revenue is consequently calculated by the time spent on sailing multiplied with the day-rate of the ship and the fraction of cargo capacity that is lost. The loss of cargo capacity is either a function of volume or mass, whichever is the largest.

$$LR_t = \frac{(OT_{gl} + OT_{seca})}{24} \cdot DR_t \cdot \frac{LC_t}{TC} \tag{5.36}$$

For a reefership, the loss of revenue is calculated by the on-hire time multiplied with the day-rate of the ship and the fraction of cargo capacity that is lost. The loss of cargo capacity is either a function of volume or mass, whichever is the largest.

$$LR_t = (365 - DDD) \cdot DR_t \cdot \frac{LC_t}{TC} \tag{5.37}$$

Besides the reduction in cargo capacity, additional bunker time may also lead to loss of revenue. This might happen when bunkering of gases can not take place simultaneously with cargo operations, due to safety restrictions. Another scenario might be that the ship has to shift to a LNG terminal to take bunkers, because LNG bunker vessels are not widely available. The time that is lost on bunker operations in such a case need to be compensated by increasing speed on the ocean stretch, leading to additional fuel consumption and costs. In the design of the model, there will not be accounted for these costs separately. The additional bunker time will change the operational profile of the ship. More time is spent in port and less time is spent at sea. This affects the time parameters related to set O, which defines the operational profile.

Carbon tax

The carbon tax in this model is related to the fuel consumption and the type of fuel that is used. The carbon tax will be calculated by the formula given in equation 5.38.

$$CT_t = CP_t \cdot \sum_{f \in F} FC_f \cdot Q_{c/f} \tag{5.38}$$

The non-dimensional factor $Q_{c/f}$ converts fuel consumption into CO_2 emissions. The conversion factor corresponds to the fuel used. The following reference values from the 'IMO guidelines on the methods of calculation of the attained EEDI for new ships' [66] are used in order to determine the relation between the carbon content in the fuel and the corresponding conversion factors. The reference values from the IMO are given in Table 5.6.

Table 5.6: Relation between carbon content and carbon conversion factor [66]

Fuel type	***Carbon content***	***Conversion factor***
Diesel / Gas oil	0.8744	3.206
Light Fuel Oil	0.8594	3.151
Heavy Fuel Oil	0.8493	3.114
Liquified Petroleum Gas	0.8182	3.000
Liquified Natural Gas	0.7500	2.750
Ethanol	0.5217	1.913
Methanol	0.3750	1.375

A scatter plot of those reference values is shown in Figure 5.2. The scatter plot can be used in order to conduct a regression analysis and find the relation between the carbon content in the fuel and the corresponding factors so that the calculation method can be applied to any particular fuel. The carbon content remains in that case as a variable and should be copied from the sample analysis of the fuel.

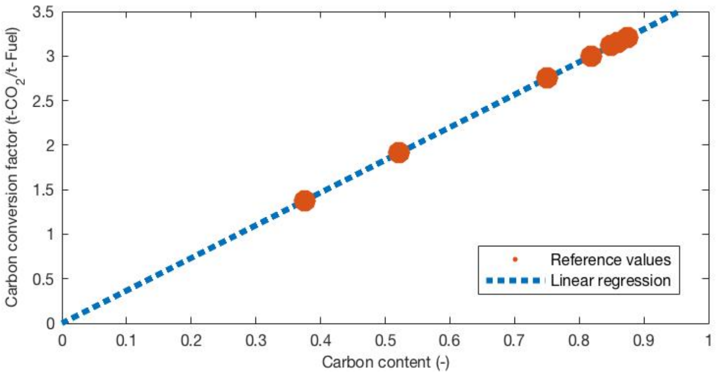


Figure 5.2: Linear regression analysis on carbon content and conversion factor

Linear regression analysis shows a direct connection between the carbon content in the fuel and the carbon conversion factor. The mathematical relation between those two parameters is found to be:

$$Q_{c/f} = 3.6663 \cdot CCF_f + 0.0002 \tag{5.39}$$

5.3. Constraints

In an optimization model, constraints minimize the feasible solutions that are subject to the objective function. The constraints that are applicable to the optimization model of this thesis are described and explained in this section. Constraints are divided into engine constraints, fuel constraint, abatement technique constraints, emission constraints and binary constraints.

Engine constraints

To select an engine type, the objective function is subjected to these engine specific constraints:

$$\sum_{e \in E} \alpha_{t,e} = 1 \qquad t \in T \tag{5.40}$$

$$\sum_{e \in E} \gamma_{t,e} = 1 \qquad t \in T \tag{5.41}$$

$$\alpha_{t,e} \geq \gamma_{t,e} \qquad t \in T, e \in E \tag{5.42}$$

$$\alpha_{t,e} + \gamma_{t-1,e} \geq \gamma_{t,e} \qquad t \in T, e \in E \tag{5.43}$$

Constraints 5.40 require that only one engine type can be installed or retrofitted in each time period. Constraints 5.41 ensure that only one engine type can be used at each time period. Constraints 5.42 and 5.43 couple the constraints 5.40 and 5.41. Constraints 5.42 ensure that if an engine type will be installed or retrofitted, the engine type must also be used in that particular time step. Constraints 5.43 ensure that if an engine type is used in a particular time step, the engine type has either already been used in the time step prior to the considered time step or is installed/retrofitted to this engine type in the same time step.

Fuel constraints

The specific constraints related to the fuel types are:

$$\epsilon_{t,o,f} = 0 \qquad t \in T, f \in F \backslash F_e \tag{5.44}$$

$$\sum_{f \in F_e} \epsilon_{t,o,f} = 1 \qquad t \in T, o \in O \tag{5.45}$$

$$\sum_{f \in F_e} \epsilon_{t,o,f} \leq M \cdot \alpha_{t,e} \qquad t \in T, e \in E \tag{5.46}$$

Constraints 5.44 require that the selected fuel types that are not compatible with the engine will not be used. Only one fuel type can only be used in any operational profile for each time period, this is ensured by constraints 5.45. Consistency between the selected engine and fuel type in any time period is ensured by constraints 5.46. The large numbers M are used to enforce that engine e is selected if a fuel type is selected for this engine in any time period.

Abatement technique constraints

The specific constraints related to the abatement techniques are:

$$\beta_{t,a} = 0 \qquad t \in T, a \in A \backslash A_e \tag{5.47}$$

$$\delta_{t,a} = \sum_{t'=max\{1,t-L_a+1\}}^{t} \beta_{t',a} \qquad t \in T, a \in A \tag{5.48}$$

$$\sum_{a \in A_e} \beta_{t,a} \leq M \cdot \alpha_e \qquad t \in T, a \in A \tag{5.49}$$

Constraints 5.47 ensure that the selected abatement technique is compatible with the selected engine. Constraints 5.48 ensure that an abatement technique will be present onboard from the installation time to the end of the lifetime. An abatement technique can only be installed together with an engine type that is selected, this is ensured by constraints 5.49. The large numbers M are used to enforce that engine e is selected if an abatement technique is installed in any time period.

Emission constraints

The objective function is subjected to emission constraints to ensure that emission regulations are met, and that compatibility issues on emission controls are taken into account.

$$R_f \cdot \epsilon_{t,o,f} + R_a \cdot \delta_{t,a} \geq G_{t,o,k} \qquad t \in T,\, o \in O,\, k \in K \tag{5.50}$$

$$\frac{\sum_{i \in I_{EEDI}} EO_{ref,i} \cdot Q_i \cdot SFC_{ref,i} - \sum_{a \in A_{EEDI}} R_k \cdot EO_{ref,i} \cdot Q_i \cdot SFC_{ref,i} \cdot \beta_{t,a}}{DWT \cdot v_{ref}} \leq B \qquad i \in I_{EEDI},\, t = 1,\, k = CO_2 \tag{5.51}$$

Constraints 5.50 ensure that the emission reduction goals are met for each time period and for each emission type. Constraints 5.51 ensure that the vessel design is complying with the EEDI regulation, meaning that the attained index is at most the required index.

Binary constraints

Binary constraints impose binary requirements on all variables.

$$\alpha_{t,e} \in \{0,1\} \qquad t \in T,\, e \in E \tag{5.52}$$

$$\beta_{t,a} \in \{0,1\} \qquad t \in T,\, a \in A \tag{5.53}$$

$$\gamma_{t,e} \in \{0,1\} \qquad t \in T,\, e \in E \tag{5.54}$$

$$\delta_{t,a} \in \{0,1\} \qquad t \in T,\, a \in A \tag{5.55}$$

$$\epsilon_{t,o,f} \in \{0,1\} \qquad t \in T,\, o \in O,\, f \in F \tag{5.56}$$

$$fr \in \{0,1\} \tag{5.57}$$

5.4. Conclusion

This chapter has given the mathematical description of the optimization model. The models on emission control installation decisions of Balland et al. [10] [11] have been used as a starting point and are extended and adjusted to the case of Seatrade. The primary difference is the use of the NPV, which is not taken into account by Balland et al. but has a major effect on net result of the analysis. The model is adjusted to the eye of a ship owner, which does not want to consider only the major costs such as engine costs, fuel expenses and costs of abatement techniques. In addition, also the secondary costs such as financing costs, additional crewing costs, changes in port charges, loss of revenue and the possibility to account for carbon taxes are included in this model. By means of the case studies in the next chapters, the model will be verified and validated. The model will be the method to obtain the final objective, which is the determination of a cost effective life-cycle strategy of the Seatrade fleet.

6

Market analysis

This chapter shows a market analysis on emission compliance methods and fuel prices. The market analysis on emission compliance is mainly focused on the sulphur regulations, because these regulations are the first upcoming and may have a major impact on the running costs of a ship. As the main part of the step-wise implementation is already enforced, conclusions can be drawn based on experiences from the past. A fuel price analysis will be done to get insight in the pricing of marine fuels. Based on common used price benchmarks, a future outlook will be given up till 2050. These projections can be used in the case studies. A SWOT analysis is conducted to get insight in the influence of the market opportunities and threats to the strengths and weaknesses of the compliance methods, risks that does not become clear by the evaluation of the deterministic decision-support tool. In the last section, the market perspective is linked to the perspective of Seatrade. There will be shown which effects the ship types, age of the fleet and operational profile of the company will have on the compliance choices.

6.1. Emission compliance

The first emission regulation that enters into force is the global sulphur cap on the 1st of January 2020. The costs of the IMO's regulatory change on the shipping industry is unknown to the shipping market, but many analysts expects it to be large [112]. As regards technology, the main choices for shipowners in order to comply with the 2020 sulphur regulations are:

- Switch to low sulphur fuel oil.
- Install a scrubber.
- Switch to LNG.

This section gives a historical review of these main compliance choices. It also gives an outlook to which choice the market tend to shift and what the mainstream choice is expected to be.

6.1.1. Historical review

In 2015, the sulphur limits were also lowered, but only applied in SECAs. In the years towards this local sulphur cap, eyes were on the shipowners and a significant uptake of LNG and scrubbers was expected [135]. However, the scrubber market is still far from booming and orders for LNG fuelled ships hold off, mainly because of the global crude oil collapse and added financial uncertainty [13]. Table 6.1 shows the compliance methods of the world merchant fleet sailing inside SECAs in 2015, after the enforcement of the new SECA sulphur limit. The size of the fleet operating in SECAs is based on figures from the Lloyd's List [94]. Only 211 ships were equipped with scrubbers and even less ships were able to burn LNG. The main conclusion that can be drawn from the enforcement in 2015 is that the availability of distillates was uncritical, because there was barely compliance default [28]. The uncritical availability is mainly the result of an ongoing shift towards increased distillate production and lower residual fuel oil production by the refineries [28].

Table 6.1: Uptake of compliance methods in 2015

	Low sulphur fuels	***Scrubbers***	***LNG***
Fleet	22,727	211	76
% of SECA fleet	98.75%	0.92%	0.33%

Figure 6.1 shows the number of ships equipped with scrubbers per year. The number of scrubbers per ship might be more than one in some cases. The count includes both newbuilding and retrofitted ships. Approximately 40% of the number of ships equipped with scrubbers are newbuilding projects, 60% of the installed scrubbers is retrofitted afterwards [32]. The largest uptake of scrubbers is seen in the approach to the 2015 sulphur limit, when the number of vessels with scrubbers more than fourfold in two years time. Ship types with the largest scrubber uptake are cruise ships, which took account for 33% of the scrubber ships operating at the end of 2017 [32] [23]. Other ship types with a significant share of the total installed scrubbers are Ro-Ro ships (16%), car/passenger ferries (12%) and tankers (12%).

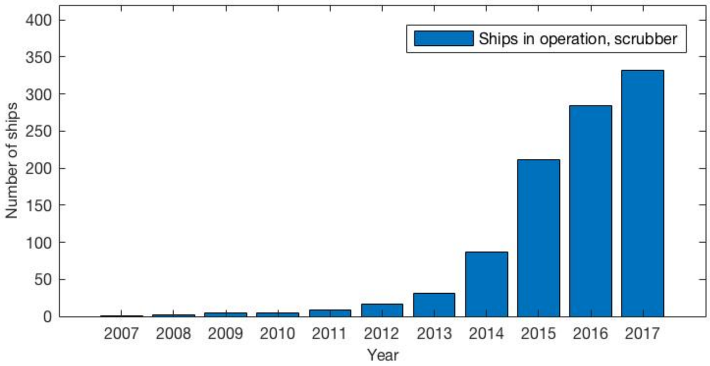


Figure 6.1: Uptake of scrubbers 2007-2017 [32]

Since the first use of scrubbers in the marine industry, open loop scrubbers were the most popular because the capital cost for this scrubber type are significant lower, no chemical additives are needed and sludge disposal is no issue. However, since some countries banned the use of open loop scrubbers in their territorial waters, among which California, Germany and Belgium, the hybrid scrubbers are increasingly gaining terrain over open loop scrubbers [13] [158]. Hybrid scrubbers have the advantage to be flexible in operation. Wherever possible, the scrubber is able to operate in open loop with low operating costs. Wherever required, the scrubber is able to operate in closed loop, which still has an economic advantage with respect to the use of low sulphur fuel oil. Figure 6.2 shows the scrubber types that are currently in operation [32].

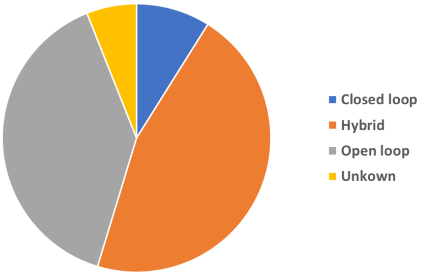


Figure 6.2: Scrubber technology 12/2017 [32]

In 2012, DNV GL predicted that by 2020, the fleet fuelled by LNG would be around 1000 vessels. Three years later, this figure was revised downwards to between 400 and 600 vessels as a result of both endogenous and exogenous factors. The primary influencing endogenous factor is the low oil price. The primary influencing exogenous factor is the slower than expected development of the bunkering infrastructure [30]. A risk, caused by the low uptake of scrubbers is the availability of high sulphur fuel oil after 2020. If the demand of the fuel burned by scrubbers is not sufficient, bunker suppliers will rather use their bunker ships for the supply of low sulphur fuel, where the demand will be significant higher.

At the end of 2017, there were 118 ships burning LNG [32]. In addition, 54 ships are classified as LNG ready, which means that engines have the possibility to be converted to LNG and space is reserved for the placement of LNG storage tanks. Today, over 70% of the ships using LNG are operating in Europe, especially in Norway [32]. Only 12% of this fleet is operating worldwide. Figure 6.3 shows the uptake of vessels fuelled by LNG. In the last 5 years, a growth of 30% on average was observed and LNG as alternative fuel is slowly starting to emerge.

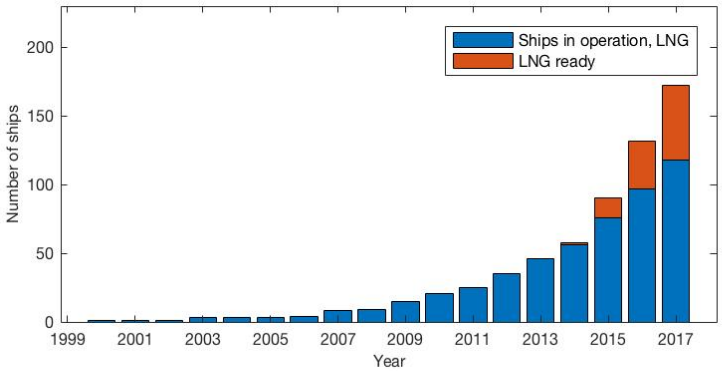


Figure 6.3: Uptake of LNG 1999-2017 [32]

Figure 6.4 shows the engine technology that is used by the ships in operation and fuelled by LNG. The biggest part of the LNG fuelled fleet is equipped with dual-fuel main engines. Only one gas turbine is in operation. The remaining share is covered by ships with pure gas engines and ships equipped with both pure gas and Diesel engines for propulsion [32].

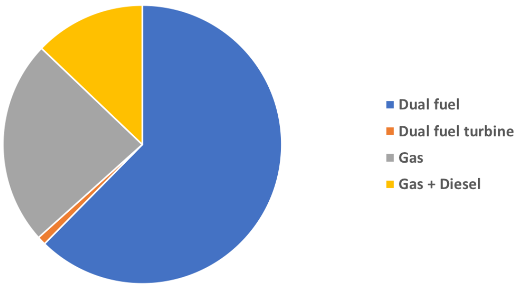
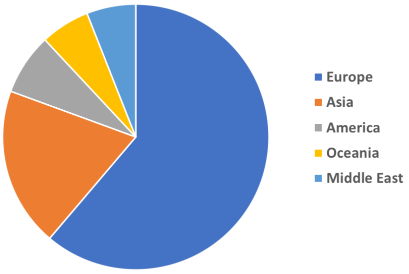


Figure 6.4: Gas engine technology in operation 12/2017 [32]

Today, one big constraint that causes shipowners to withhold the use of LNG is the limited availability of LNG bunkering facilities worldwide. Figure 6.5 shows the current distribution of the LNG infrastructure, with a total of 67 locations. There may be several bunkering facilities on one location. Table 6.2 gives insight in the bunker facilities that were in operation at the end of 2017. Local storage is the most available facility and includes an intermediary LNG storage, which is used for further distribution and storage for an industrial user. Direct LNG bunkering from tank to ship is not necessarily feasible on this locations and is counted separately. A truck loading facility is a terminal where LNG trucks can receive LNG and where in fact LNG bunkering via trucks is possible. A bunker ship loading facility is a terminal where small LNG carriers have access to receive LNG. The most important bunker facility for ships is a bunker vessel, providing the most efficient way of bunkering and limiting the additional port time required for bunkering. At the end of 2017, only 4 LNG bunker vessels where available and were all operating in Europe [32].

Figure 6.5: Distribution of LNG infrastructure [32]



Facility type	***In operation***
Local storage	44
Bunker ship loading facility	13
Tank to ship	29
Truck loading	43
Bunker vessel	4

Table 6.2: LNG bunker facilities in operation 12/2017 [32]

6.1.2. Future outlook

The ships in the order book suggest that the majority of ships will meet the new sulphur limits by switching to low sulphur fuels in the short term. A small share of the existing fleet and the order book is reported to have scrubbers installed. At the end of 2017, 84 scrubbers were in the order book [32]. LNG as fuel has better expectations, based on the order book. At the end of 2017, 126 LNG fuelled ships were in the order book, which means more than a doubling of the current LNG fuelled fleet [32]. In addition, 60 ships in the order book will be made LNG ready. Figure 6.6 gives insight in the differences between ship types. The number of ships represent both installed ships and ships in the order book. The most striking difference between scrubbers and LNG is observed for cruise ships, which has obviously no space to place the LNG storage tanks without largely affecting the capacity.

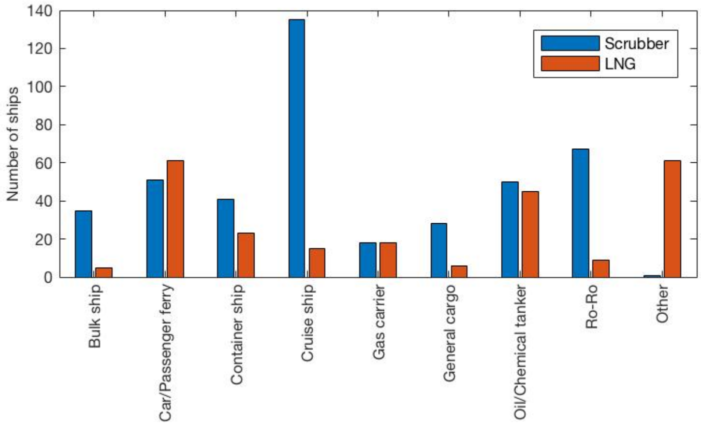


Figure 6.6: Comparison scrubbers and LNG [32]

Bunkering facilities for LNG are expanding on a global scale. At this moment, there is decided to built 60 facilities worldwide and at least 69 facilities are under discussion, according to DNV GL's LNGi business intelligence portal [32]. Table 6.3 shows the facility types that are decided and under discussion. Despite the fact that there will be a large increase of facilities in the upcoming years, more than half of the projects is planned in Europe and will not convince ship owners operating worldwide to use LNG. 2 out of 5 planned bunker vessels will be located in America. The remaining 3 bunker vessels are being built for Europe. Major suppliers including Total, Shell, Gas Natural Fenosa, ENN and Statoil have indicated that they are considering new LNG bunker vessels, which are likely to materialize at key locations in Northern Europe, the Middle East, the Gulf of Mexico, Singapore, and the Mediterranean [30].

Table 6.3: LNG bunker facilities decided & under discussion 12/2017 [32]

Facility type	***Decided***	***Under discussion***
Local storage	22	27
Bunker ship loading facility	8	5
Tank to ship	16	20
Truck loading	12	12
Bunker vessel	5	1

Table 6.4 gives the projected uptake of the compliance methods up to 2020, based on the order book of December 2017 [32]. The size of the global fleet is based on the Review of Maritime Transport 2017 from the UNCTAD [116]. The conclusion that can be drawn from this projection is that the absolute number of scrubbers and LNG in the global merchant fleet will increase. Compared to the figures from 2015 as shown in this chapter, the number of ships with scrubbers will increase by 83% and the number of ships fuelled by LNG will be tripled. Although, the relative share of the entire global fleet remains very limited.

Table 6.4: Projected uptake of compliance methods up to 2020

	Low sulphur fuels	***Scrubbers***	***LNG***
Fleet	49,514	414	227
% of global fleet	98.72%	0.83%	0.45%

The number of ships that are subject to the 2020 sulphur regulations is 4 times bigger than the number of ships that were subject to the 2015 SECA sulphur regulations. Therefore, the fact that there was no low sulphur fuel supply issue in 2015 will not guarantee sufficient low sulphur fuel supply in 2020. A study is done by CE Delft in order to assess the availability of low sulphur fuels in 2020 and advice the IMO. EnSys Energy and Navigistics Consulting have been concerned that any single study would generate debate and adding a second study could reduce uncertainty and place the IMO in a stronger position to make a sound decision. Accordingly, EnSys and Navigistics have undertaken a supplemental marine fuels availability study with the aim of providing additional insight and a second opinion to inform the IMO.

The study from CE Delft has developed three scenarios, a base case with moderate transport demand growth, fleet renewal, LNG and scrubber uptake, a high case with higher transport demand growth and fleet renewal and lower uptake of scrubbers and LNG, so that the demand for compliant fuel is larger, and a low case which is the mirror image of the high case [43]. In the base case, an annual global demand of 320 million tonnes is forecasted for 2020. Of this, 85% will be for fuel with a maximum sulphur content of 0.1%, whilst 11% of demand will be HSFO and 4% LNG. The analysis results in all cases to the conclusion that the refinery sector can produce sufficient compliant fuels to meet demand. All compliant fuels are blends of several refinery streams. The blend varies per region, depending on regional refinery capacity and crude inputs. While globally, supply and demand are balanced regional shortages and surpluses will occur. The Middle East is expected to have an oversupply that can be transported to other regions to offset regional shortages [43].

EnSys and Navigistics have also considered different scenarios and have concluded that in the central case, an annual global demand of 342 million tonnes is forecasted for 2020. Of this, 83% will be low sulphur fuels, 14% HSFO and 3% LNG [38]. So far not much difference with the study of CE Delft. Also the refining unit capacity projections are generally similar between the two studies. Both studies recognize that the hydrogen production that is required for desulphurizing and the sulphur recovery unit capacities will be critical. However, the differences between both studies are the assumptions made, causing the conclusions to contrast sharply with each-other [75]. CE Delft assumes that refineries will make sure that adequate capacities will be in place, by doing investments. EnSys makes a detailed analysis on the likelihood of availability. EnSys concludes that the capacity limitations would prevent the refinery industry from supplying the volumes needed to achieve full compliance with the 2020 sulphur regulations. Even in the most optimistic case in which sufficient sulphur removal capacity is available, the industry could potentially meet the global volumes but with a substantial increase in supply costs. The increase of supply costs will not be limited to marine fuels but applies also to nearly all fuels, except HSFO [38].

6.2. Fuel prices

The fuel price development of the past years will be analyzed to get insight in the correlation between the different fuels. With this information, a substantiated future fuel price trend can be suggested that can be used in the case studies. The correlation of the historical oil and gas prices will be assessed using Pearson's correlation coefficient. This coefficient shows the statistical linear relationship between two trend lines [109]. The generic definition of the Pearson's correlation coefficient ($\rho(A,B)$) is given in equation 6.1 for the trend lines A and B. In the equation, μ and σ are the mean and standard deviation and N represents the number of measurements.

$$\rho(A,B) = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{\overline{A_i - \mu_A}}{\sigma_A}\right)\left(\frac{B_i - \mu_B}{\sigma_B}\right) \tag{6.1}$$

6.2.1. Historical review

There are many different varieties and grades of fuel oil. To assess the oil price in general, crude oil is usually used as benchmark. There are three primary benchmarks: Brent, Dubai and West Texas Intermediate (WTI) [4]. Brent is a mix of crude oil from 15 different oil fields in the North Sea and is primarily used in Europe. The Dubai Crude represents crude oils from the Persian Gulf and is also used as a benchmark for lubrication oils. The WTI benchmark is primarily used in the United States and is mainly a pricing benchmark rather than it has production output [4]. Figure 6.7 shows the price development of the three primary oil benchmarks between 1999 and 2017. The trend shows, after a few years of high but stable oil prices, a sharp downturn of prices in 2014 [148]. In 2016, the Brent Crude price fell down to a yearly average of 45 \$/bbl [16]. There can be concluded from the graph that the three benchmarks are linked to each other and the differentials between the crudes from different areas are not significant. The correlation coefficients of the crude oil benchmarks are given in Table 6.5. All correlation coefficients are above 0.98, which means that the benchmarks are very strong correlated and do not diverge from each other.

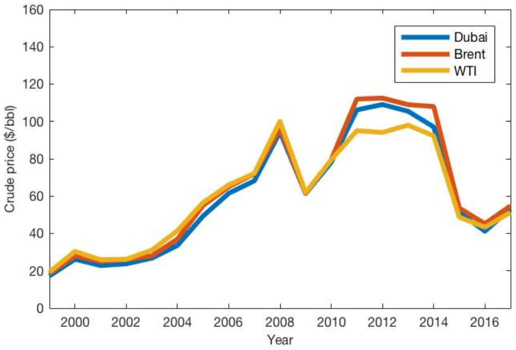


Figure 6.7: Price development crude oil benchmarks [16]

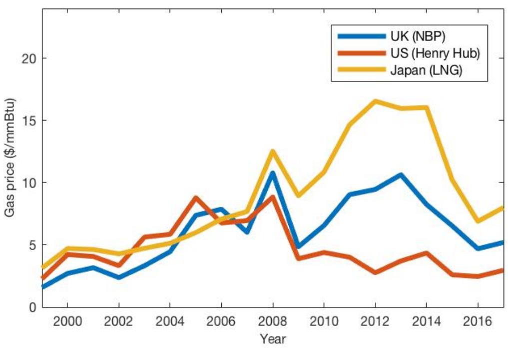


Figure 6.8: Price development natural gas benchmarks [85]

The opposite is the case for the pricing of natural gas, which has the United States Henry Hub, United Kingdom NBP index and Japanese LNG price as primary benchmarks [61]. With no global price benchmark for natural gas, the gas price formation is based on regional markets [148]. The development of those three benchmarks between 1999 and 2017 is given in Figure 6.8. The trend shows a price convergence in the past years, after a price divergence in the periods of high oil prices [148]. Based on Figure 6.8, it can be concluded that the correlation between the natural gas benchmarks is not that strong as it is with the crude oil benchmarks. The United States Henry Hub price is based on gas to gas competition in a largely closed market. Similar to the United States Henry Hub, the United Kingdom NBP index is formed by gas to gas competition, but is also influenced by the European energy prices [148]. The natural gas prices in Asia are represented by the Japanese LNG price and are in the past most dominated by the crude oil prices. This is also reflected in the correlation coefficients, shown in Table 6.6. The correlation coefficients show that only the United Kingdom NBP index and the Japanese LNG price are clearly correlated with a coefficient of 0.866. The correlation between the United Kingdom NBP index and the United States Henry Hub is moderate but still existing. The correlation between the United States Henry Hub and the Japanese LNG price is very weak because it has a negative correlation coefficient.

Table 6.5: Correlation coefficients crude oil benchmarks

	Dubai	***Brent***	***WTI***
Dubai	1.000	0.998	0.987
Brent	0.998	1.000	0.984
WTI	0.987	0.984	1.000

Table 6.6: Correlation coefficients natural gas benchmarks

	UK	***US***	***Japan***
UK	1.000	0.337	0.866
US	0.337	1.000	-0.077
Japan	0.866	-0.077	1.000

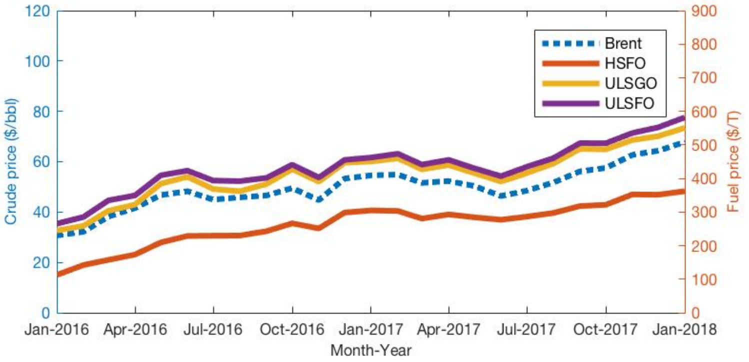


Figure 6.9: Price development of marine fuels [140]

Figure 6.9 gives the price development of marine fuels of a two year period. The given price levels represent the spot price in Rotterdam with supply costs included. The Brent benchmark is given as reference. It is clear that there is a strong link between the marine fuels and the Brent benchmark. The correlation coefficients are given in Table 6.7. Given these correlation coefficients, there can be concluded that HSFO, ULSGO and ULSFO are very strong correlated to the Brent Crude benchmark. VLSGO and VLSFO are not analyzed because the fuels are not on the market yet and no historical data is available. VLSGO and VLSFO are expected to enter the market when the new sulphur cap of 2020 comes into force.

Table 6.7: Correlation coefficients marine fuels

	Brent	***HSFO***	***ULSGO***	***ULSFO***
Brent	1.000	0.940	0.981	0.974
HSFO	0.940	1.000	0.965	0.976
ULSGO	0.981	0.965	1.000	0.997
ULSFO	0.974	0.976	0.997	1.000

As already discussed, the natural gas price development varies per area and the correlation between the benchmarks is not so strong as it is the case for crude oil. The LNG price in the United States is very strong linked to the United States Henry Hub benchmark. This is proven by Figure 6.10, which shows the price development between 2009 and 2018 in the United States. A correlation coefficient of 0.933 is calculated, which means that the United States Henry Hub benchmark and the United States LNG prices are very strong correlated. Supply costs are included in the LNG pricing. Despite that these costs may vary per area and depend on the size of the LNG bunker terminal, the average supply costs of 2.8 \$/mmBtu is taken for all LNG prices [25].

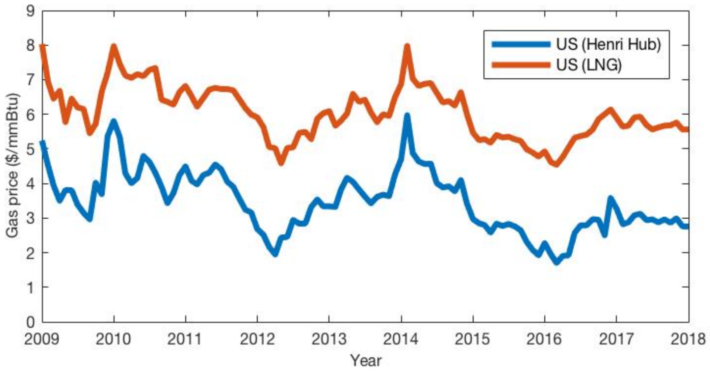


Figure 6.10: Price development of US gas [16] [86]

In contradiction to the LNG price in the United States, the LNG price in Asia is correlated to the crude oil benchmarks. This is proven by Figure 6.11, which provides the price development between 2009 and 2018. A strong link can be observed, which is endorsed by the correlation coefficient, which is 0.858 between the Japanese LNG price and the Brent benchmark. A time delay of approximately 4 months is observed in the graph for the Japan LNG price, something what the correlation coefficient does not take into account. The correlation coefficient is 0.990 when the values are corrected for the time delay. The LNG price includes 2.8 \$/mmBtu of supply costs [25].

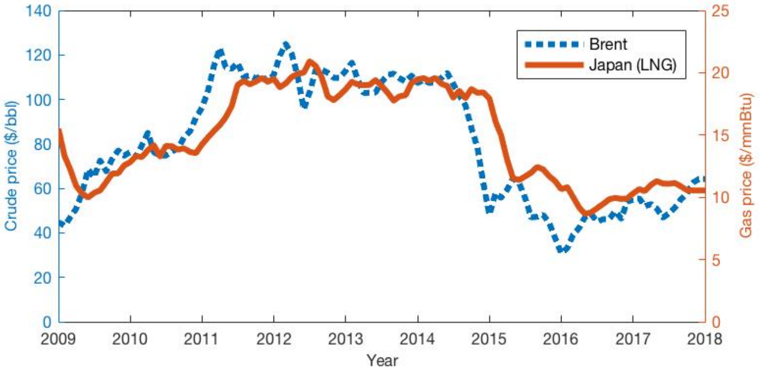


Figure 6.11: Price development of Japan LNG [16] [140]

Figure 6.12 gives the price development of natural gas from the United Kingdom. The trend of the United Kingdom gas price is somewhere in the middle of the United States and Japanese gas trend. The United Kingdom LNG price has a correlation coefficient of 0.758 with the Brent benchmark, which implicates that there is certainly a connection between both indices. The LNG price includes 2.8 \$/mmBtu supply costs [25].

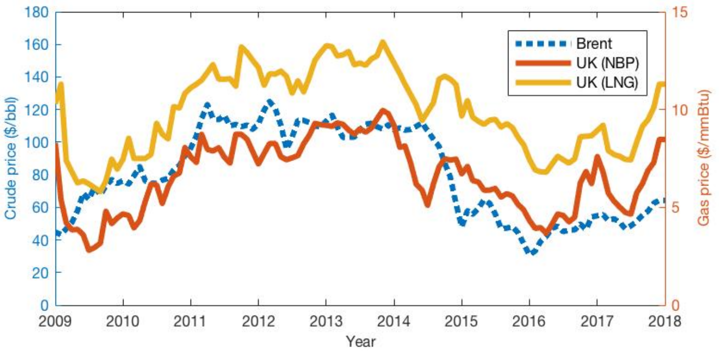


Figure 6.12: Price development of UK gas [16] [86]

In the past, the gas prices were always linked to the oil prices. Analysts declare that due to increased supply and weakened demand of natural gas, the gas prices have started to decouple from the oil price in the United States, which might be strengthened by the uptake of shale gas [61]. The same occurs now in Europe and is expected to occur in Asia in due time. The correlation coefficients related to the different gas benchmarks are given in Table 6.8.

Table 6.8: Market analysis, correlation coefficients natural gas and LNG

	US (Henry Hub)	***US (LNG)***	***Japan (LNG)***	***UK (NBP)***	***UK (LNG)***	***Brent***
US (Henry Hub)	1.000	0.935	0.322	0.181	0.185	0.391
US (LNG)	0.935	1.000	0.242	0.106	0.118	0.322
Japan (LNG)	0.181	0.242	1.000	0.733	0.821	0.149
UK (NBP)	0.185	0.106	0.733	1.000	0.931	0.701
UK (LNG)	0.391	1.118	0.821	0.931	1.000	0.758

From the historical data, it became clear that the conventional marine fuels have a very strong link with the crude oil benchmarks. As the crude oil benchmarks does not diverge between themselves, it makes not much difference which benchmark is used in the further analysis. In the further analysis, the Brent Crude will be used as benchmark for the oil based marine fuels. For the natural gases, the United States Henry Hub will be used as benchmark for the LNG price in the America continents. The United Kingdom NBP index will be used as benchmark for LNG in Europe and the Brent Crude will be used for the LNG price in Asia.

6.2.2. Future outlook

Several institutes provide an annual energy outlook for the future and their expectations on the energy consumption and fuel prices. The long term fuel price expectations are usually given with respect to the primary oil- or natural gas benchmarks and are usually closely related to the supply and demand. Something what is similar for all institutions, is the expectation that the global energy landscape will change in the coming years and will consist of a broader mix of energy sources [17]. For shipping, this includes the shift from the conventional fuel oils to renewable resources such LNG and biofuels [37]. The expectations from DNV GL on the energy transition in the maritime industry are given in Figure 6.13. The relative fuel oil and gas oil demand will drop from 94% in 2017 to 47% and LNG and biofuels will make an upswing, according to DNV GL [37].

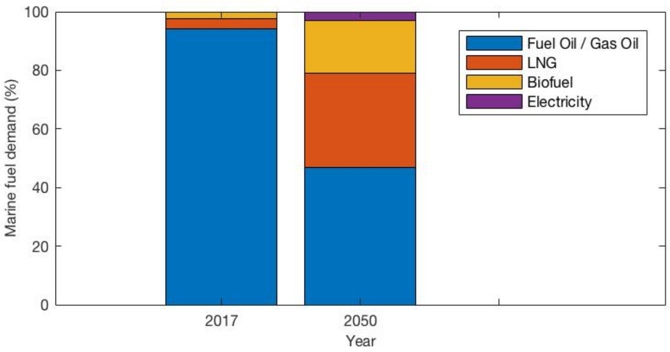


Figure 6.13: Relative marine fuel demand 2017 vs. 2050 [41] [37]

Figure 6.14 gives the outlook of the oil price from three different institutes. All three outlooks are composed by the use of a market based approach. The results are not predictions of what will happen, but rather modeled projections of what may happen given certain assumptions and methodologies [149]. The first outlook is from the U.S. Energy Information Administration, which has provided a scenario that reaches an oil price of 121 $/bbl in 2050. Up to 2040, the fuel prices are pushed up by increasing demand. By then, the cheap sources of oil will have been exhausted, making it more expensive to extract oil [149]. The reasons for the unchanged price levels after 2030 are the long term uncertainties [148]. The future price scenario of the UK Gov. is obtained by intersected supply and demand curves, to arrive at long term equilibrium prices. The third scenario is given by the World Bank, which gives a market outlook every six months. The outlook from October 2017 is used in Figure 6.14. The World Bank describes in their scenario a decreased energy demand, which causes the prices to drop. Due to the significant deviation between the three outlook scenarios, large volatility is expected.

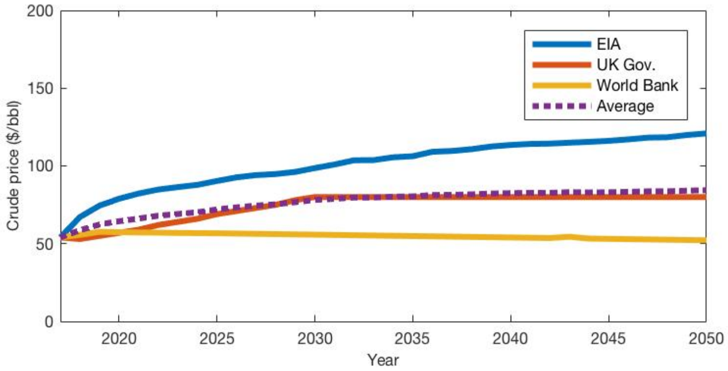


Figure 6.14: Future outlook Brent crude prices [149] [159] [148]

Figure 6.15 gives the outlook of the natural gas prices at the Henry Hub from three different institutes. The observation when considering the graph, is that the three scenarios look very similar and expect a steady growth of 1.8% on average. The U.S. Energy Information Administration, that describes the first scenario, declares that the net export growth moderates, domestic natural gas use becomes more efficient and prices slowly rise [149]. Rising prices are moderated by assumed advances in the natural gas extraction technologies. Comparing the natural gas forecast with the crude oil forecast from the U.S. Energy Information Administration, the oil prices are expected to grow faster than the natural gas prices. The second scenario is described by the World Bank, which expects a relative slow short term increase of the natural gas prices compared to the other scenarios [159]. The third scenario is from Statista, which expects that the natural gas will account for the increased energy demand. On the first hand because it is a more mature technology than most renewable energy sources, on the other hand because gas is seen as much more environmentally friendly than coal, nuclear sources or crude oils [141]. Due to the close link between the three scenarios, high volatile prices are not expected.

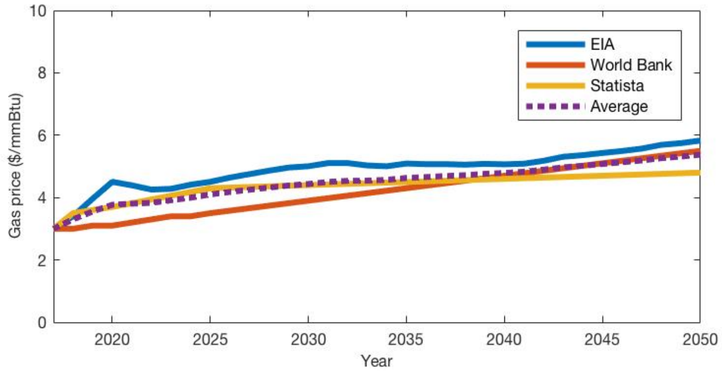


Figure 6.15: Future outlook U.S. Henry Hub prices [149] [159] [141]

Figure 6.16 gives the outlook of the natural gas price in Europe, reflected by three scenarios of the United Kindom NBP index future trend. In the short term outlook up to 2020, global LNG capacity is expected to grow strongly and the global market is expected to be well supplied. From 2020 to 2035, the price increase is driven by increased energy demand. In comparison to the United States Henry Hub price outlook, the medium term prices for the United Kingdom NBP index are more coupled to the oil prices. In the long term, the decreasing energy demand will flatten the increase of prices. The second scenario is described by the World Bank and is somewhat more nuanced in their expectations of the uptake of natural gas. The third scenario is described by Statista and shows a steep rise of the prices up to 2025, driven by the replacement of oils for natural gas in the transportation sector, including shipping [141]. The infrastructure is expected to develop faster in Europe than in America. The increase of the United Kingdom NBP index looks comparable to the expectations for the United States Henry Hub. However, prices of the NBP index are expected to remain almost twice the prices of the Henry Hub.

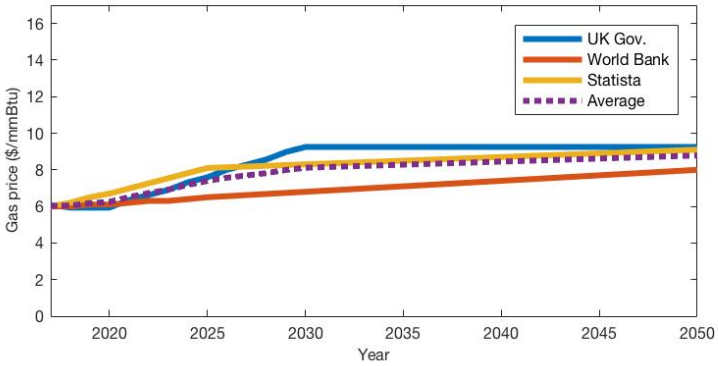


Figure 6.16: Future outlook U.K. NBP prices [159] [141] [148]

The prices in Figures 6.14, 6.15 and 6.16 are real values, meaning that the values have been corrected for inflation. Wherever small deviations in the 2017 price level were present between the scenarios, the forecasts are corrected to the same price level in 2017. The price level in 2017 for the Brent Crude was 54 $/bbl, for gas from the United Kingdom Henry Hub 3 $/mmBtu and for gas from the United Kingdom NBP index 6 $/mmBtu. The forecasts from the UK Gov. and the World Bank did not cover the entire period to 2050. In those cases, the remaining period is extrapolated from the given data.

The average trend of the fuel price forecasts will be coupled to the marine fuels to obtain a substantiated price scenario of the marine fuels up to 2050. The relations between the Brent Crude oil price level and the prices of HSFO, ULSGO and ULSFO are obtained from historical data. From historical data, it also become clear that the LNG prices strongly depend on the area that is considered. Therefore, distinction is made between the areas when considering the LNG prices. The LNG price in the United States will be referred to the United State Henry Hub price level, the LNG price in Europe will be referred to the United Kingdom NBP index and the LNG price in Asia will be referred to the Brent Crude oil price. The relations that can not be obtained by historical data are the relations of VLSGO and VLSFO with benchmarks, because these fuels does not yet exist. As there is expected that the majority of these fuels will be obtained by blending, the expectations for these fuels will be based on the blending rate [78]. The equation that determines the VLSFO price is given in equation 6.2.

$$VLSFO\,price = HSFO\,price \cdot blending\,rate + ULSFO\,price \cdot (1 - blending\,rate) \tag{6.2}$$

The HSFO does normally have a maximum sulphur content of 3.5% and the ULSFO does normally have a maximum sulphur content of 0.1%. The blending rate needs to be 118/882 if the VLSFO will end up with a sulphur percentage of 0.5%. Considering the expected 2020 fuel prices, HSFO will cost 336.5 $/MT, ULSFO will cost 527.7 $/MT. By putting the values into the equation, a VLSFO price of 505.1 $/MT is expected. The forecast for VLSGO will be related to the differential between ULSFO and ULSGO. The two yearly average differential between ULSFO and ULSGO is obtained from Figure 6.9 and is found to be 4.7%. The same differential will be used for the difference between VLSFO and VLSGO.

Table 6.9 gives the conversion factors from the oil and gas benchmarks to the marine fuels in \$/T. This price unit will be used as input for the model. This however means that the prices are not corrected for the difference in LHV. Correction for the energy content will be done in the optimization method. The conversion factors from S&P Global Platts are used to convert the Brent Crude price from \$/bbl to \$/T and to convert the LNG prices from \$/mmBtu to \$/T [139]. Supply costs are included in the pricing of the marine fuels.

Table 6.9: Conversion factors fuels and benchmarks prices

Fuel	***(Unit)***	***Reference***	***(Unit)***	***Conversion factor***
HSFO	*(\$/T)*	Brent	*(\$/bbl)*	5.222
ULSGO	*(\$/T)*	Brent	*(\$/bbl)*	8.575
ULSFO	*(\$/T)*	Brent	*(\$/bbl)*	8.189
VLSGO	*(\$/T)*	Brent	*(\$/bbl)*	8.158
VLSFO	*(\$/T)*	Brent	*(\$/bbl)*	7.792
LNG US	*(\$/T)*	US Henry Hub	*(\$/mmBtu)*	90.655
LNG EU	*(\$/T)*	UK NBP index	*(\$/mmBtu)*	77.899
LNG Asia	*(\$/T)*	Brent	*(\$/bbl)*	0.184

To directly compare fuel prices, it is more convenient to correct the prices for the energy content. Figure 6.17 gives the fuel prices per energy unit in \$/mmBtu. The unit \$/MWh could also have been used, which can be obtained by multiplying the unit \$/mmBtu with a factor 3.4118. The LNG price is very dependent on the area. The LNG price in America is expected to be sold with a discount of approximately 50% on the low sulphur oils, based on the future curves shown in this chapter. The discount in Europe compared to low sulphur oils is 20% and the price of LNG in Asia is projected to be in the same range of low sulphur fuels, which is caused by Chinese and Japanese deals, weather-driven demand and tight supply [153]. The differential between the different low sulphur oils is very limited, only up to 5%. Remarkable is that the price of gas oil per energy unit is lower than the corresponding low sulphur fuel oil. Local impacts on the fuel price differential as a result of the 2020 sulphur cap of the IMO are not considered. Developments such as the 2020 sulphur cap may result in extreme variations on the fuel prices in the short term. However, the market is expected to rebalance on medium to long term [21].

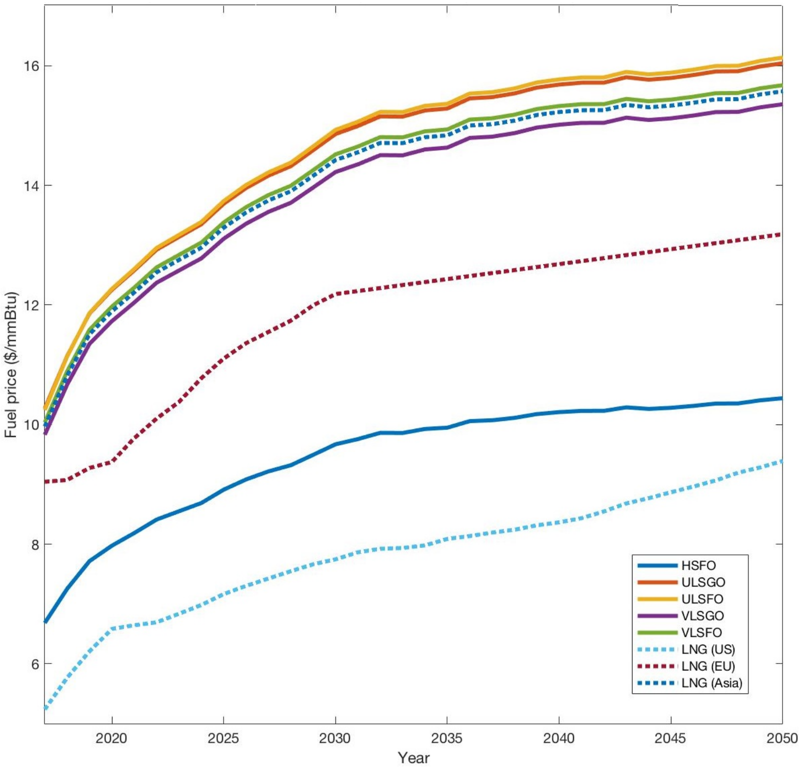


Figure 6.17: Marine fuel price forecast

6.3. SWOT analysis

A SWOT analysis is conducted to evaluate strengths, weaknesses, opportunities and threats for the project. Strength and weaknesses are internal factors and relate in this case to the compliance option that is considered. Opportunities and threats are external factors from the market that might influence the internal factors either in a positive or negative manner. With a confrontation matrix, insight is obtained in the interrelation of the internal and external factors. The three main compliance options for the 2020 sulphur regulations are considered.

Table 6.10 gives the SWOT analysis of the use of low sulphur fuels. In each category, two most important factors are given. The dominant strength for this compliance options is that no additional investments are required. Existing ships are able to comply with the 2020 sulphur cap practically without investments. The major threat for this compliance option is that the price spread between HSFO and low sulphur fuels will increase significantly. Unavailability of the fuels around 2020 might be an overrated threat because the market analysis shows that almost 98.7% of the world merchant fleet will opt for this compliance option, based on orderbook figures. Instead of shutting down a part of the merchant fleet, a way out in case of unavailability may be the adoption of a Fuel Oil Non-Availability Report (FONAR), by which an operator may be allowed to burn non-compliant fuel in case the low sulphur oils are not available in the last port of call [78].

Table 6.10: SWOT analysis on low sulphur fuels

LOW SULPHUR FUELS	
Strengths	**Weaknesses**
1. Compliance with 2020 sulphur cap 2. No investments required	1. No Tier III compliance 2. Compatibility and stability issues
Opportunities	**Threats**
1. Main choice of shipping industry 2. Flexibility for additional energy efficiency measures	1. Price spread between HSFO and low sulphur fuels 2. Unavailability around 2020 when supply/demand don't match

The results of the SWOT analysis are compared in the confrontation matrix to identify the most strategic issues. The confrontation matrix for low sulphur fuels is given in Table 6.11. A plus signs means that the external factors are influencing the internal factors positively. A negative sign means that the external factors are influencing the internal factors negatively. In the case that the external factors do not influence the internal factors, a 0 is given in the confrontation matrix. The main strength is that no investments are required. However, if the the price spread between HSFO and low sulphur fuels increases, the strength that no investments are required has become a weaker advantage.

Table 6.11: Confrontation matrix of low sulphur fuels

		Strengths		**Weaknesses**	
		1	*2*	*1*	*2*
Opportunities	*1*	0	0	+	+
	2	+	++	0	+
Threats	*1*	0	- -	0	-
	2	- -	-	0	0

Table 6.12 gives the SWOT analysis of the installation of scrubbers. The price spread between HSFO and low sulphur fuels is both an opportunity and a threat. Other weaknesses and threats are minor. The fact that the current lifetime of the scrubber is shorter than the lifetime of a ship is in particular a problem when the payback time is long. For example, when the payback time is only 2 years, installation of scrubbers can still give a big advantage.

Table 6.12: SWOT analysis on scrubbers

SCRUBBERS	
Strengths	**Weaknesses**
1. Able to burn HSFO 2. Compliance with 2020 sulphur cap	1. No Tier III compliance 2. Lifetime scrubbers is shorter than lifetime ship
Opportunities	**Threats**
1. Short payback time 2. Price spread between HSFO and low sulphur fuels	1. Uncertainty about future ban of scrubbers 2. Price spread between HSFO and low sulphur fuels

The confrontation matrix of installing scrubbers is given in Table 6.13. The sum of the confrontation matrix is negative, which means that the risk of opting for this method is significant. The biggest risk of this business case is caused by the threats influencing the strength to burn HSFO. A ban on scrubbers will fully take away the most important strength. The price spread can only reduce the advantage of being able to burn HSFO. On the other hand, the benefit can be very high when the opportunities reinforce the strengths. The most potential factor is the price spread between HSFO and low sulphur fuels.

Table 6.13: Confrontation matrix of scrubbers

		Strengths		**Weaknesses**	
		1	*2*	*1*	*2*
Opportunities	*1*	0	0	0	-
	2	++	++	0	0
Threats	*1*	- -	0	0	0
	2	- -	0	0	-

Table 6.14 gives the SWOT analysis of the installation of LNG systems. The most particular strength of LNG is the compliance with NO_x Tier III, next to compliance with the 2020 sulphur cap. This option has the advantage that no additional techniques needs to be installed for Tier III compliance. This advantage is only applicable to newbuilding ships. The most significant threat is the lack of infrastructure, especially applicable to ships that do not operate on a fixed trade. This threat is expected to be resolved in medium term.

Table 6.14: SWOT analysis on LNG

LNG	
Strengths	**Weaknesses**
1. Complies with 2020 sulphur cap and NO_x Tier III 2. Use of a clean fuel requiring less maintenance	1. High initial investments 2. Loss of revenue due to storage tanks
Opportunities	**Threats**
1. Price spread between oil and LNG 2. If new regulations on CO_2 are enforced, LNG is beneficial	1. Slow development of infrastructure 2. No simultaneous bunker/cargo operations allowed

The confrontation matrix of installing a LNG system is given in Table 6.15. The sum of the confrontation matrix is positive, which means that most factors interact in a positive way with each other. The negative effect of the weaknesses may be taken away by the external opportunities. For example, the high initial investments of a LNG system are less important if the price spread between oil and LNG is high enough. An example of an external factor that negatively interact with an internal factor is the slow development of the infrastructure. If LNG is not available, compliance with both the 2020 sulphur cap and NO_x Tier III regulations is not important because the ship can not sail at all or in case of a dual-fuel, the ship has to switch to oil and does not comply anymore with NO_x Tier III regulations.

Table 6.15: Confrontation matrix of LNG

		Strengths		**Weaknesses**	
		1	*2*	*1*	*2*
Opportunities	*1*	++	++	++	+
	2	+	+	+	+
Threats	*1*	- -	- -	-	-
	2	0	-	-	0

The confrontation matrices gave insight in the risks involved in each compliance method. Comparing the results and adding the plus signs and minus signs of each compliance option leads to the conclusion that the installation of LNG systems has the most limited risk, based on the market analysis. The feasibility of this compliance option is depending on certain factors. But the potential benefit of this option is significant, being compliance with both SO$_x$ and NO$_x$ regulations and a probable head start when regulations on CO$_2$ emissions are enforced. The installation of scrubbers is appeared to be the most risky investment. However, if the opportunities become reality and the price spread between HSFO and low sulphur fuels will become sufficiently high, the advantage of scrubbers can be extremely high. The options for opting for low sulphur fuels is in terms of risk somewhere in between. The risk of an increased price spread between HSFO and low sulphur fuels and LNG is pretty high but there are no large capitals involved, which reduces the risk considerably.

6.4. Perspective of Seatrade

Seatrade operates a fleet of 87 specialized ships (dated 11/01/2018) focusing on the transport of perishables and other sensitive cargoes. The fleet consists of 82 conventional reefer ships and 5 containerships. The ships are operating in either the GreenSea reefer pool or the Seatrade reefer pool. Seatrade Groningen B.V. is the shipmanager of most vessels in the pool. Seatrade Reefer Chartering N.V. takes responsibility for the commercial part of the business. The containerships are specialized for the transport of reefer containers and are equipped with 675 reefer plugs. The age distribution of the Seatrade fleet is given in Figure 6.18. With an average of 22 years, the Seatrade fleet is relatively old and a fleet renewal program is in progress. At the beginning of 2018, 7 ships were in the order book, of which 4 specialized reefer ships, 1 refrigerated juice carrier and 2 specialized reefer container ships.

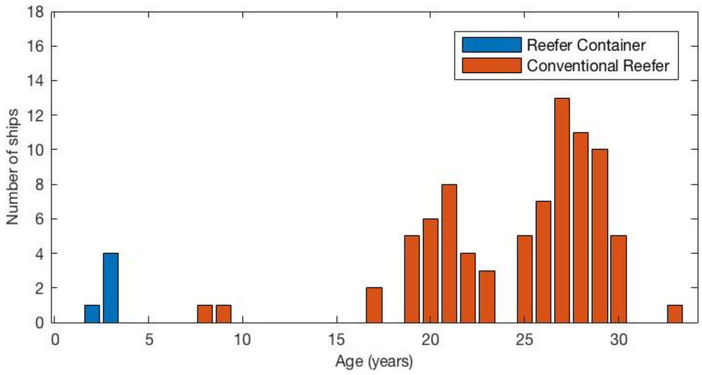


Figure 6.18: Age distribution Seatrade fleet

In the global reefer market, the trend is that a substantiated share of the the transport by conventional reefer ships is being replaced by containerships. Figure 6.19 shows the market share of the specialized reefer ships on the total refrigerated cargo. The rapid decrease in market share, in combination with the average age of the specialized reefer ships in the Seatrade fleet, might reduce the opportunities for an investment in the current fleet of Seatrade due to an uncertain payback period and large capitals involved. The trend gives also opportunities, for example for the specialized reefer container ship, which have enough payback time and a better market perspective. Also, the niche markets on products that are practically not suited for carriage in containers, such as frozen fish and refrigerated juice, give good market perspectives. These niche markets have also a confined trading area, which gives a good estimation on the operational profile during the lifetime of the ship. For containerships, the operational profile and area needs to be much more flexible.

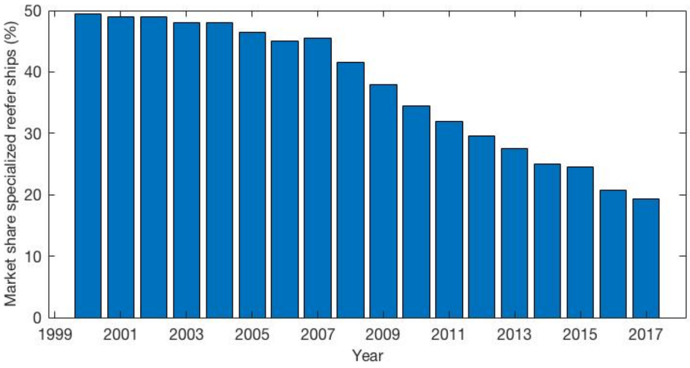


Figure 6.19: Specialized reefer market share 2000-2017 [12] [33]

In the analysis of Chapter 6.1, the specialized reefer ships fall under the ship type 'general cargo'. Specialized reefer container ships are accounted in the ship type 'containerships'. Two specialized reefer ships have been equipped with hybrid scrubbers during newbuilding. The ships are operated by EF Transport, based in Malta, and delivered in 2017 [137]. The first intention to built a specialized reefer ship fuelled by LNG is made by the shipping company Seoil Agency [108]. The ship will have a capacity of 155,000 cubic feet and will be equipped with four-stroke dual-fuel engines from Wärtsilä. No retrofits of specialized reefer vessels have been reported with scrubbers or LNG systems. As has been seen in Chapter 6.1.2, scrubbers are more popular than LNG in the container shipping industry. However, a breakthrough decision is recently made by CMA CGM, which has decided to built 9 ultra-large container ships with all equipment necessary to use LNG [106].

As the LNG price and bunker facilities strongly depend on the region, the operational area of the Seatrade fleet is analyzed. Figure 6.20 gives the operational area of the Seatrade fleet, based on port calls in 2017. 27% of the port calls are inside SECAs. The main operational area's are Europe and North America, especially the Caribbean. Bunkering takes usually place in Europe. The main bunker ports are Rotterdam, Panama, Algeciras, St. Petersburg and Las Palmas [34]. As an example, the weekly Caribanex liner service to the Caribbean calls ports in both North America and Europe but takes bunkers in Europe. When this is applied to the LNG business case, the fuel capacity needs to be sufficient for one roundtrip.

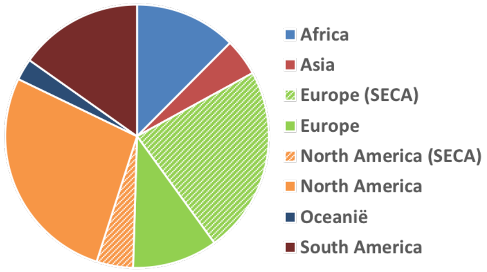


Figure 6.20: Operational area Seatrade fleet [34]

6.5. Conclusion

The market analysis on emission compliance has given a realistic representation on how the shipping market is opposed to emission compliance. The emphasis has been placed on compliance with the global SO_x regulations, the first emission regulations that shipowners will face in the next years. Based on order book figures, the expected uptake of scrubbers and LNG will be very limited. The share of the global fleet that will opt for scrubbers in 2020 is 0.8%. The hybrid scrubber type is in favor since some countries have issued a ban on open loop operation in territorial waters. The share of the global fleet that will opt for LNG in 2020 is 0.5%. The upswing of LNG is slowed down by the low oil price and slower than expected development of bunkering infrastructure. However, the newbuilding trend to make ships LNG ready is observed. In case of a rising oil price and developed infrastructure, the ship owner is able to convert the engines to dual-fuel engines and there is already space reserved for the placement of LNG storage tanks.

The historical trend of the oil and gas market is analyzed to derive the relationship between marine fuels and oil and gas benchmarks. The marine fuel oils are appeared to be closely related to the oil benchmarks. Between the different oil benchmarks, a closely related trend was observed. The opposite was the case for gas benchmarks, which showed a different trend between benchmarks of different areas. The derived relations are used to give a projection to the future, based on the common used benchmarks. Future projections on oil prices differed among different sources, which indicates a volatile price trend. Gas price forecasts were more similar to each other, which indicate a more stable price trend. The future projections of each benchmark can be used in the case studies to reflect the price forecast of marine fuels.

In the SWOT analysis, the risks of the different compliance methods are indicated. Threats and opportunities from the market are assessed to what extent these factors will affect the strengths and weaknesses of the compliance options. The analysis shows that the external factors most positively influence the LNG business case. In this case, even some weaknesses of the compliance option are taken away by external opportunities. For example, additional CO_2 measures that are probably enforced in the future are less of an influence to LNG fuelled ships, compared to the other options because LNG has already a CO_2 reduction potential of 20%, while scrubbers even have a penalty on the CO_2 emissions. The installation of scrubbers has the most potential benefit, but comes also with the greatest risk. Low sulphur fuels have no investment costs, which reduces the risk significantly. However, the risk lays in terms of fuel spread between low sulphur fuels and HSFO / LNG.

The market analysis is coupled to the perspective of Seatrade. The analysis have shown that the age of the specialized reefer vessels is relatively high and that the renewal of the fleet is focused on niche markets and container ships with more reefer plugs than standard containerships. The Seatrade fleet is operating worldwide, especially the ships with a changing worldwide operational profile are restricted in obtaining LNG. For ships that have a fixed operational profile, the fuel capacity needs to be sufficient to cover an entire voyage. The reason is that the main bunker ports of the fleet, and also most LNG bunker facilities, are located in Europe.

The market analysis has gained insight in the movements of the market, which may add or remove a substantiated part of the risk involved in the choice of compliance methods. For example, the development of the bunkering infrastructure for LNG is of crucial importance when considering LNG as compliance option. If LNG is not available in the operational area that is considered, this option can be removed immediately. This chapter has indicated those crucial factors, that are not part of a deterministic decision-support model, but certainly important.

7

Case study 1: Freezer

The ship that will be discussed in this case is still in the design phase. The abatement options will be considered for installing during newbuilding. Therefore, later installation of abatement techniques is not considered. Obviously, the reality strongly depends on the development of new regulations, price developments and availability of the fuels. In this case study, the model as defined in Chapter 5 will be validated and verified. The case will be introduced before the cost & data analysis defines the cost parameters that will be used in this case. Next, the results are presented. A deterministic approach is used and requires a sensitivity analysis to get insight in they key parameters and their influence on the results. In appendices C till E, an elaboration on the input data, results and sensitivity analysis is given.

7.1. Case description

The ship that will be considered in this case study is a freezer vessel, intended to be used for the transshipment of frozen fish, transportation of citrus fruits and potatoes. A graphic representation of the initial design is given in Figure 7.1. The vessel has a length over all of 114.4 metres and a summer draft of 7.6 metres. The hold capacity is 310,000 ft^3. The size of the ship restricts the possibility of installing large sized abatement techniques to a reasonable degree. The engine that will be installed at newbuilding has to remain the entire commercial lifetime onboard, thus no engine conversion need to be considered. The intended commercial lifetime of the ship is 30 years.

Figure 7.1: Freezer ship

With the propulsion power requirement of 3325 kW, 15 knots should be obtained at MCR, taken into account a sea margin of 15%. The MCR is the maximum output that can be produced by the engine continuously without causing failure to the propulsion machinery [88]. As specified in the building specifications, the speed is based on the vessel design with a fixed pitch propeller, clean hull in deep water, no currents, no waves. The installed electric power requirement is 2500 kW. Due to space requirements, this power requirement should be distributed over 4 power generators. The average electric power consumption is 518 kW at sea and 645 kW in port. Those figures are taken from the standard voyage calculations that are used within Seatrade as a performance benchmark.

The options for emission compliance will be limited in this case study to the engines, fuels and abatement techniques that are listed in Table 8.2. Fuel cells in combination with hydrogen will not be considered because the development on this technique is not yet there. The concept is proven in practice but not all technical challenges are covered, for example the large volumes that are required for storage. Biofuels are also not considered in this case study. Biofuels are currently more expensive than conventional fuels and can be used in the future as a replacement of those fuels. However, they do not contribute to compliance with the regulations and do not add more value to the analysis if they are taken into account. The WHRS is not taken into the analysis because this abatement technique is only considered profitable for large power requirements. Since the freezer ship that will be considered in this case study is a relatively small ship, the WHRS is exempted by technical constraints.

Table 7.1: Considered compliance options

Engines	***Fuels***	***Abatement Techniques***
Diesel Engine	HFSO	EGR
Dual-Fuel Engine	ULSFO / GO	Scrubber
Gas Engine	VLSFO / GO	SCR
	LNG	

A standard voyage that is used by Seatrade for calculations on similar ships will reflect the operational profile of the ship. The voyage data, including the port slots, is given in Table 7.2. Due to the operational profile of the ship and economic considerations, the selection of a fixed pitch propeller and directly mounted shaft to the main engine is already decided.

Table 7.2: Voyage schedule

#	***Port***	***Total distance***	***Distance SECA***	***Arrival (GMT)***	***Departure (GMT)***
1	IJmuiden (Netherlands)	-	-	01-Jan 08:00	05-Jan 20:00
2	Lagos (Nigeria)	4184 nm	424 nm	19-Jan 06:00	27-Jan 18:00
3	Abidjan (Ivory Coast)	473 nm	0 nm	29-Jan 06:30	18-Feb 06:30
4	Puebla d. Caraminal (Spain)	2879 nm	0 nm	27-Feb 12:00	22-Mar 12:00
5	IJmuiden (Netherlands)	924 nm	437 nm	25-Mar 11:00	29-Mar 23:00

Reduction on port charges is neglected in this case study. The discount that may be obtained in ports by having a high Environmental Ship Index (ESI) is very uncertain and is often retroactively defined.

7.2. Cost & data analysis

In this analysis, the values that are used as input for the model are given and substantiated with previous researches, as indicated. The required input data is divided into finance related, engine related, fuel related and abatement related parameters.

Finance related

The shipbuilding industry is seeing order books decline rapidly at this moment [127]. The need for contracting to pick up has become urgent for many yards. This has its implications for the possible finance methods. A disappointing market means that banks and financial institutions are reluctant to provide loans. Mezzanine finance will not be used for this case study because this type of finance is commonly used in times of a booming economy, which is not the case at this moment [5]. On the other hand, seller's credit is more often offered in order to provide shipyards with orders. The used financial structure in this case study is given in Table 7.3. Only the financial structure for a newbuilding project is given because retrofit is not considered. The discount rate that will be used for the NPV method is 5%.

Table 7.3: Finance sources newbuilding

Finance source	***Share***	***Repayment type***	***Interest rate***	***Tenor***
Owner equity	20%	-	-	-
Senior debt	70%	Yearly repayment	4.5%	10 years
Mezzanine debt	0%	-	-	-
Seller's credit	10%	Balloon repayment	6.0%	10 years

Engine related

In order to obtain representative values for the engine costs in this analysis, an average of three sources is taken. Among the sources are previous researches, but also recent quotations requested by Seatrade. The average capital costs of a conventional Diesel engine are found to be 371.0 \$/kW and include installation costs. The values and sources that are used to obtain this average value are given in Table 7.4. The costs of installation are assumed to be 120 \$/kW and constant for all engine types [25]. This is only the case for a newbuilding project [42]. When considering a retrofit project, the costs of installation will change.

Table 7.4: Diesel engine capital costs including installation

Engine costs	*Source*
372.0 \$/kW	CE Delft & TNO [42], DMA [25]
368.9 \$/kW	Levander [91]
372.1 \$/kW	Ventura [151]
371.0 \$/kW	**Average**

The values and sources that are used in order to determine the average costs of a dual-fuel engine are given in Table 7.5. These costs include the costs for the engine, generators, electric system and installation. The cost of the fuel supply system and tanks are not included. A dual-fuel engine with low-pressure injection is considered, which requires no additional abatement techniques for NO_x Tier III compliance [42].

Table 7.5: Dual-fuel engine capital costs including installation

Engine costs	*Source*
387.5 \$/kW	Balland [9]
408.0 \$/kW	DMA [25]
394.6 \$/kW	GDF Suez [45]
396.7 \$/kW	**Average**

The values and sources that are used in order to determine the average costs of a gas engine are given in Table 7.6. Similar to the data for a dual-fuel engine, the engine, generators, electric system and installation are included in the costs. The costs of the fuel supply system and tanks are not included. Gas engines for marine propulsion are not widely available at this moment. Due to the limited available cost data for marine applications, also costs of land based engines are used (Power Technology) [123]. It is trivial that there will be a discount on the gas engines compared to the dual-fuel or Diesel engines, because the gas engines are four-stroke engines and thus much lighter in weight than two-stroke engines.

Table 7.6: Gas engine capital costs including installation

Engine costs	*Source*
450.0 \$/kW	DMA [25]
372.3 \$/kW	Power Technology [123]
341.6 \$/kW	Power Technology [123]
388.0 \$/kW	**Average**

There is no difference between the LNG gas storage system of a dual-fuel engine and a gas engine. The cost of the storage system is not related to the installed power and can better be approached by an expression in $\$/m^3$. The values and sources that are used in order to determine the cost of a gas supply and storage system are given in Table 7.7.

Table 7.7: Capital costs of a gas supply and storage system

LNG gas system	*Source*
7488.4 $\$/m^3$	GDF Suez [45]
5555.6 $\$/m^3$	Balland [9]
8571.4 $\$/m^3$	Seatrade [22]
7205.1 $\$/m^3$	**Average**

The maintenance costs for a Diesel engine are estimated at 1.5 $/MWh [59]. This is a weighted value based on specific maintenance costs of 1 $/MWh for two-stroke main engines and 2.5 $/MWh for four-stroke auxiliary engines. For a gas engine, the maintenance costs are approximately 35% lower, as gas combustion is significant cleaner than its fuel oil counterparts [136]. Approximately 15% of the maintenance costs of a gas engine accounts for the maintenance of the gas storage and vaporization system [50]. The dual-fuel engine does not take rid of the fuel oil maintenance and accounts also for the maintenance costs of the gas storage and vaporization system. Therefore, the maintenance costs for a dual-fuel engine will be higher than both the Diesel engine and the gas engine. The maintenance costs that are used in this case study are given in Table 7.8.

Table 7.8: Maintenance costs

Engine	***Maintenance costs engines***	***Source***
Diesel Engine	1.5 $/MWh	IDMEB [59]
Dual-Fuel Engine	1.7 $/MWh	MAN B&W [100]
Gas Engine	1.0 $/MWh	Ge & Wang [46]

The engines have different specific fuel consumptions compared to each other. The fuel consumption curves as given in Figure 5.1 of Chapter 5.2.3 are used. This figure only gives relative fuel consumptions. The specific fuel consumption rates at 100% MCR need to be defined and are given in Table 7.9. Distinction is made between two-stroke engines and four-stroke engines. For Diesel engines and dual-fuel engines, this is also the difference between main engines and auxiliary engines. For gas engines, both the main and auxiliary engines are considered as four-stroke engines because there are no two-stroke pure gas engines available. The gas engine in general is more efficient but a four-stroke gas engine is not more efficient than a two-stroke Diesel or dual-fuel engine. The LHV where these specific fuel consumption rates are related to is in all cases 42.7 MJ/kg. A dual-fuel engine in gas mode has a specific fuel consumption which is 1 g/kWh lower than operating in Diesel mode. This specific fuel consumption is considered, because if a dual-fuel engine is installed, LNG will be used as fuel. There is no use to install a dual-fuel engine and do not use LNG as fuel.

Table 7.9: Specific Fuel Consumption at 100% MCR

Engine	***Two-stroke***	***Four-stroke***	***Source***
Diesel Engine	175.0 g/kWh	187.0 g/kWh	Seatrade [133]
Dual-Fuel Engine	174.0 g/kWh	186.0 g/kWh	MAN B&W [103]
Gas Engine	-	181.4 g/kWh	MTU [114]

Fuel related

Typical lower heating values of the considered fuels are given in Table 7.10. Lower heating values of oils depend mainly on the distillated fraction. Lower heating values of LNG are very much depending on the geographic area and ranges from 49.0 to 49.9 MJ/kg [158]. The average of the worldwide energy content is used, which is 49.4 MJ/kg [158].

Table 7.10: Lower Heating Values

Fuel	***LHV***	***Source***
HSFO	40.0 MJ/kg	Wild [155]
ULSGO	42.7 MJ/kg	Wild [155]
ULSFO	40.0 MJ/kg	Wild [155]
VLSGO	42.7 MJ/kg	Wild [155]
VLSFO	40.0 MJ/kg	Wild [155]
LNG	49.2 MJ/kg	Marine Fuels & Emissions [158]

The costs of consumables are reflected as the consumption of lubrication oil multiplied with the price of the lubrication oil. The lubrication oil rate is assumed to be constant for all engines and will be 0.5 g/kWh. Each fuel type requires an appropriate lubrication oil, which mainly depends on the Total Base Number (TBN). The TBN mainly depends on the quantity of acids in the fuel, among which sulphur. The prices for different lubrication oils vary per type and are therefore taken into account. The appropriate lubrication oils for the different fuel types are given in Table 7.11. Also, the TBN and prices are given. Multiplication of the lubrication oil price with the consumption rate, divided by the volumetric density gives the total costs of consumables in the unit $/MWh.

Table 7.11: Costs of consumables

Fuel	*Lubrication type*	*TBN*	*Price*	*Volumetric density*	*Source*
HSFO	Mobilgard 570	70	1.14 $/L	937 kg/m^3	Seatrade [134], ExxonMobil [40]
ULSGO	Mobilgard 525	25	2.03 $/L	909 kg/m^3	Seatrade [134], ExxonMobil [40]
ULSFO	Mobilgard 560 VS	60	1.30 $/L	922 kg/m^3	Seatrade [134], ExxonMobil [40]
VLSGO	Mobilgard 525	25	2.03 $/L	909 kg/m^3	Seatrade [134], ExxonMobil [40]
VLSFO	Mobilgard 560 VS	60	1.30 $/L	922 kg/m^3	Seatrade [134], ExxonMobil [40]
LNG	Mobil SHC Pegasus	5	1.81 $/L	850 kg/m^3	Seatrade [134], ExxonMobil [40]

The waste from the settling and purification of fuel is disposed as sludge, which usually comes with disposal costs. All vessels using oils as fuel produce sludge, but the amount of sludge that comes from distillates is much less than the case using residuals [20]. CE Delft performed a study on the generated waste onboard ships in which is given an indication of the amount of sludge that is produced with different fuels. The sludge production per fuel type is given in Table 7.12.

Table 7.12: Sludge production

Fuel	*Amount of sludge*	*Source*
HSFO	1.5% of fuel consumption	CE Delft [20]
ULSGO	0.5% of fuel consumption	CE Delft [20]
ULSFO	1.0% of fuel consumption	CE Delft [20]
VLSGO	0.5% of fuel consumption	CE Delft [20]
VLSFO	1.1% of fuel consumption	CE Delft, based on blending rates [20]
LNG	0.0% of fuel consumption	CE Delft [20]

Remaining parameters related to fuels are the carbon contents and reduction potentials. The standard carbon contents as given in Table 5.6 of Chapter 5.2.3 are used. The reduction potentials of the fuels will be used as given in Figures 3.9, 3.10, 3.11 and 3.12 of Chapter 3.3, except the CO_2 reduction potential of LNG. This reduction potential strongly depends on the engine type. In this case study, two-stroke engines are considered, which reduce the CO_2 reduction potential of CO_2 to 20% when using LNG.

Abatement technique related

In order to obtain representative values for the capital costs for abatement techniques, an average of three sources is taken. Among the sources are previous researches, but also recent quotations requested by Seatrade. The average capital costs for an EGR system are 49.6 $/kW, including installation. The values and sources that are used are given in Table 7.13. Typically, 15% of the costs are installation costs [26]. The lifespan of the system is assumed to be equal or greater than the operational lifetime of the ship.

Table 7.13: EGR capital costs including installation

EGR costs	*Source*
48.0 $/kW	Winnes et al. [157]
51.7 $/kW	Parsmo et al. [118]
49.2 $/kW	Danish Ministry of the Environment [26]
49.6 $/kW	**Average**

The scrubber type that is considered is a hybrid scrubber, as the use of an open loop scrubber is already banned by different countries. The ban might be implemented by more countries in due time, which should reduce the benefits of installing an open loop scrubber significantly. The average capital costs of a hybrid scrubber are 174.5 $/kW, including installation. The values and sources that are used are given in Table 7.14. Typically, 43.7 $/kW of the costs are designated to installation of the equipment [9]. The technological developments on scrubbers are currently still going on. At this time, the lifetime of scrubbers is approximately 15 years [156]. This time period is used for the analysis.

Table 7.14: Hybrid scrubber capital costs including installation

Scrubber costs	***Source***
178.7 $/kW	Alfa Laval [110]
166.1 $/kW	Gu & Wallace [54]
178.7 $/kW	Hansen et al. [57]
174.5 $/kW	**Average**

The average capital costs for a SCR system are 54.5 $/kW, including installation. The values and sources that are used are given in Table 7.15. Typically, 20% of the capital costs are installation costs [26]. The lifetime of the system is assumed to be equal or greater than the operational lifetime of the ship.

Table 7.15: SCR capital costs including installation

SCR costs	***Source***
54.0 $/kW	CE Delft & TNO [42], DMA [25]
50.4 $/kW	Danish Ministry of the Enviroment [26]
59.2 $/kW	Campling et al. [19]
54.5 $/kW	**Average**

Only the options for installing the abatement techniques at newbuilding will be considered. All emission reduction potentials of the abatement techniques as discussed in Figures 3.9, 3.10, 3.11 and 3.12 of Chapter 3.3 will be used. For the hybrid scrubber, a CO_2 reduction potential of -1.0% is taken into account [27]. The maintenance costs of the abatement techniques are given in Table 7.16. In the literature, no difference is made between the maintenance costs of different scrubber types. Maintenance costs of the SCR system mainly consist of the catalyst replacement [157].

Table 7.16: Maintenance costs of abatement techniques

	Maintenance costs	***Source***
EGR	0.1 $/MWh	Hansen et al. [57]
Scrubber	0.3 $/MWh	den Boer & ’t Hoen [27]
SCR	0.7 $/MWh	Bosch et al. [15]

The costs of consumables related to the operation of abatement techniques are given in Table 7.17. For the EGR, some consumable costs are accounted for, as the EGR is fitted with a small scrubber to remove particulates and sulphur before recirculating the exhaust gas back into the cylinder. The scrubber has no consumables when operating in open loop mode. In closed loop mode, the consumables mainly consist of the chemicals used in the wash water to neutralize the SO_x particles, which amounts 4.0 $/MWh [104]. In the calculations, a weighted average is taken corresponding to the energy consumption inside SECAs and outside SECAs. Inside SECAs, the scrubber is assumed to operate in closed loop mode while outside SECAs, the scrubber is assumed to operate in open loop mode. The thought behind this is that SECAs might be the first areas that restrict the use of the open loop mode. Currently, the open loop mode is only prohibited in Belgium, Germany and California [158]. Urea is the consumable that is taken into account for the operation of a SCR system.

Table 7.17: Consumable costs of abatement techniques

	Consumable costs	***Source***
EGR	1.5 $/MWh	Parsmo et al. [118]
Scrubber, open loop	0.0 $/MWh	den Boer & ’t Hoen [27]
Scrubber, closed loop	4.0 $/MWh	MAN B&W [104]
SCR	2.7 $/MWh	Parsmo et al. [118]

The costs of sludge disposal related to the operation of the abatement techniques are given in Table 7.18. The sludge disposal costs are 30 \$/T, according to the Port of Rotterdam [122]. The sludge production of an EGR system is very minor, which is also the case for a scrubber operating in open loop mode. A scrubber operating in closed loop mode has significant more sludge production compared to a scrubber operating in open loop mode. A SCR system does not have any sludge production.

Table 7.18: Sludge production by abatement techniques

	Sludge production	***Source***
EGR	0.1 kg/MWh	Winnes et al. [157]
Scrubber, open loop	0.2 kg/MWh	Entec [52]
Scrubber, closed loop	2.5 kg/MWh	Lahtinen [89]
SCR	0.0 kg/MWh	Parsmo et al. [118]

The weight of an EGR unit will be neglected, as no additional weight has been taken into account in other researches, in contradiction to scrubbers and SCR systems. The weight of a hybrid scrubber is approximately 1800 kg/MW, which gives a total weight of 10.5 T for this business case [104]. The weight of a SCR system is typically 900 kg/MW, which gives a weight of 5.2 T for this case study. These weights will be taken into account for calculating the loss of revenue.

Table 7.19: Weight of abatement techniques

	Weight	***Source***
EGR	0.0 T/MW	n/a
Scrubber, hybrid	1.8 T/MW	MAN B&W [104]
SCR	0.9 T/MW	Liljegren [92]

7.3. Results

In this analysis, 8 compliance options are considered, as shown in Table 7.20. The ship will become operational in 2021 and the only NECA the ship operates in is the NECA in Europe. Therefore, the ship does not have to comply with the Tier III NO_x regulations, because the keel laying date will be before 2021. Nevertheless, the options that meet Tier III requirements will also be considered to be more flexible in changing the operational area, because in the United States, Tier III compliance is required for ships with a keel laying date before 2016. The options 1 and 3 from Table 7.20 are not meeting Tier III requirements. In compliance option 7, a dual-fuel engine with low pressure injection is considered. Low pressure injection dual-fuel engines are usually somewhat more expensive compared to high pressure injection dual-fuel engines, according to TNO & CE Delft [42]. The benefit of this engines is that the engine does not require the installation of additional abatement techniques to meet Tier III requirements. In addition to the 8 compliance options, a benchmark is given which represents the situation as it was before 2020, using high sulphur fuels outside SECAs and using ultra low sulphur fuels inside SECAs. This benchmark is given in order to be able to assess the costs change as a result of the 2020 sulphur cap.

Table 7.20: Considered options & compliance

#	***Engine***	***Abatement Techniques***	***Tier III compliance***	***SO_x compliance > 2020***
0	Diesel Engine	-	No	No
1	Diesel Engine	-	No	Yes
2	Diesel Engine	EGR	Yes	Yes
3	Diesel Engine	Scrubber	No	Yes
4	Diesel Engine	SCR	Yes	Yes
5	Diesel Engine	EGR + Scrubber	Yes	Yes
6	Diesel Engine	Scrubber + SCR	Yes	Yes
7	Dual-Fuel Engine	-	Yes	Yes
8	Gas Engine	-	Yes	Yes

With the given voyage schedule, the operational profile of the ship can be determined. This operational profile is the same for all alternatives, except for the alternative using LNG as fuel. For this alternative, additional port time is accounted because no bunker operations are allowed simultaneously with cargo operations. The general operational profile, without accounting for additional bunker time, is given in Figures 7.2 and 7.3.

Figure 7.2 shows the part of the time that the ship is in port, sailing inside SECAs and outside SECAs. There can be concluded that the ship spent extraordinary much time in port. The reason is that the ship carries mainly frozen fish, which results in very large loading and discharging times. A very small part of the time is spent on sailing inside SECAs. The absolute times spent in the different areas is given in Figure 7.3. Also the service speeds that are required by the voyage schedule is given, which is 13.0 knots for every leg. Speed optimization is applied to obtain the most economical speeds inside SECAs and outside SECAs. However, speed optimization did not result in significant changes of the speed for this case study.

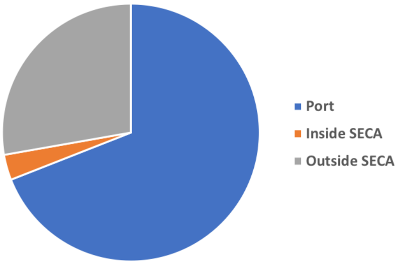


Figure 7.2: Relative time profile

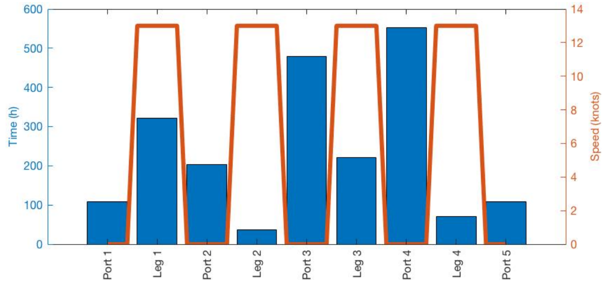


Figure 7.3: Operational profile, time and speed

The total energy demand per voyage is 2681.3 MWh, without power correction factor due to the installation of abatement techniques. Taking into account the specific fuel consumptions and the lower heating value of LNG (49.2 MJ/kg), the total power demand equals a LNG consumption of 405 T. An average volumetric density of 450 kg/m^3 is used to obtain the corresponding LNG volume of 900 m^3 [115]. In order to obtain the required tank size, 5% engine consumption margin, 15% safety buffer and 85% tank utilization are used, in line with the assumptions of Balland [9]. Taking those assumptions into account, the required tank size is 1270 m^3. The bunkering port for this case study is IJmuiden, where the Flex Fueler from Titan LNG is able to deliver LNG with a barge. This barge is able to deliver LNG with a bunker speed of 600 m^3/h can be obtained [145]. Simultaneous operations might be possible under restricted conditions. However, for this case study, there will be assumed that this is not possible because it is still a grey area. 2 hours of additional port time is accounted, which will be compensated on the stretch from IJmuiden to Lagos. The alternative is bunkering by truck, which seems to be not a feasible solution, as this goes usually with a rate of 60 m^3/h and simultaneous operations is not possible. In that case, 18 hours additional port time is required, which is out of acceptable limits.

Obviously, each compliance option uses the cheapest compatible fuel in the calculations. This can mean that a dual-fuel engine will not run on LNG, when the running costs of low sulphur fuels will drop below the running costs of LNG. Table 7.21 gives for each case the fuel that is used, both inside and outside SECAs. Remarkable is that for compliance options using scrubbers, the fuel choice changes to low sulphur fuels after 15 years, when the operational lifetime of a scrubber has expired. For other options, the fuel choice is the same for every year during the lifetime of the ship. A notable observation is that the low sulphur gas oils are selected, instead of the low sulphur fuel oils, which have a discount on the gas oils. However, the discount on low sulphur fuel oils with respect to low sulphur gas oils is only 5.5%, while the energy content in low sulphur gas oils is 6.5% higher. Despite the fact that low sulphur gas oils are encountering some additional consumable costs, the running costs of low sulphur gas oils are still lower than for low sulphur fuel oils.

Table 7.21: Fuel choice for compliance options

#	***Fuel, global***	***Fuel, SECA***
0	HSFO	ULSGO
1	VLSGO	ULSGO
2	VLSGO	VLSGO
3	HSFO	HSFO
4	VLSGO	ULSGO
5	HSFO	HSFO
6	HSFO	HSFO
7	LNG	LNG
8	LNG	LNG

Figure 7.4 shows an overview of the results, a cost comparison for 30 years. The initial capital that is needed is not significant, because 80% of the capital expenses are financed by senior debt and seller's credit, which both have a duration of 10 years. That is the reason why the slope of the Net Present Cost (NPC) curve is clearly different in the first 10 years compared to the last 20 years. The options where a scrubber is installed appeared to be the most cost effective choice, with a positive net difference after 2 years. The actual payback time is somewhat longer because after 2 years, the financing is not paid off. For the calculation of the nominal payback time, financing and the time value of money are not considered, thus the discount rate of the NPV analysis is set to 0%. This results in a payback time of 4.0 years for the installation of a scrubber. The discounted payback time, where financing is neglected but the discount rate is taken into account is 4.5 years. The options using LNG are clearly separated from the options using oils, they are never beneficial compared to the conventional Diesel engine in this case study.

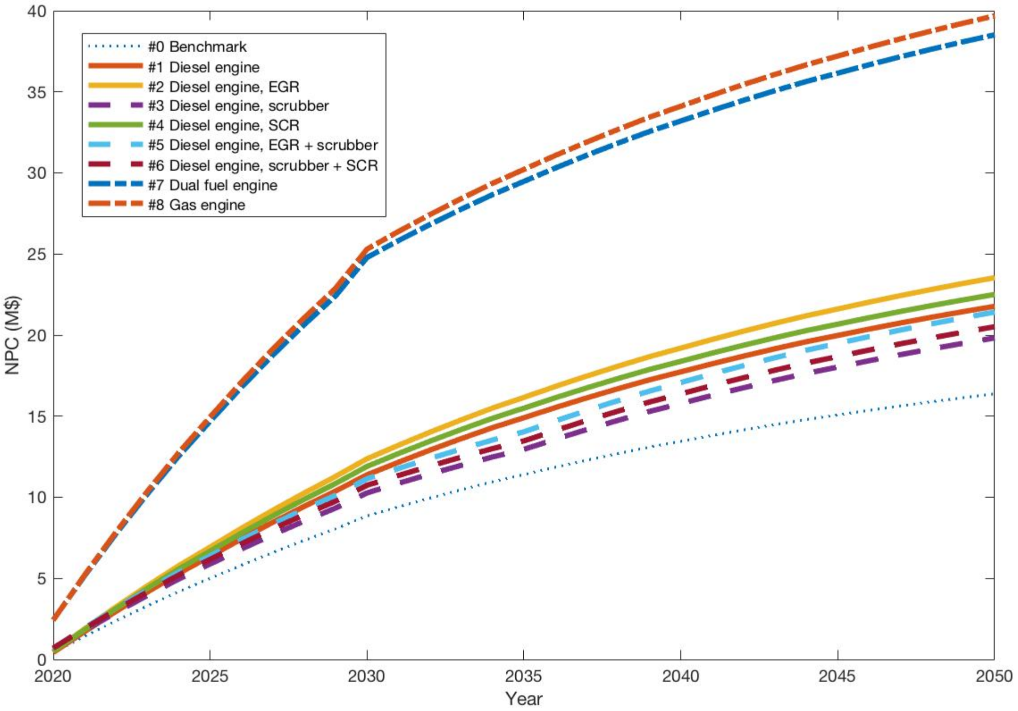


Figure 7.4: Total life-cycle costs

Figure 7.5 gives the life-cycle costs related to emission compliance of each option, subdivided into CAPEX, OPEX and voyage expenses. The scrubber, used in the first 15 years of options 3, 5 and 6, has higher capital costs and operational expenses, but reduces the voyage expenses, which results in a net reduction of costs. The NO$_x$ reduction techniques EGR and SCR require investments, but do not result in a reduction of operational costs or voyage expenses. These techniques result in higher voyage expenses, because they have a penalty on the fuel consumption. Dual-fuel and gas engines have significant more investment costs, more operational costs and more voyage expenses.

Table 7.22: Total life-cycle costs

#	***Total life-cycle costs***
0	16.38 M$
1	21.78 M$
2	23.54 M$
3	19.83 M$
4	22.51 M$
5	21.43 M$
6	20.53 M$
7	38.52 M$
8	39.68 M$

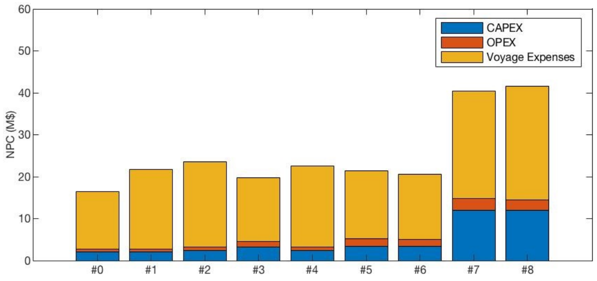


Figure 7.5: Subdivision of life-cycle costs

The capital expenses are given in Figure 7.6 and separated into costs related to engines, abatement techniques and financing. The discount rate is higher than the average finance costs, therefore discounted finance costs are negative and deducted from the total capital costs. In the sensitivity analysis, it becomes more insightfull when the financing has a negative or positive effect on the net result. The increased CAPEX for dual-fuel engines and gas engines is mainly a result of the relative expensive gas storage tanks.

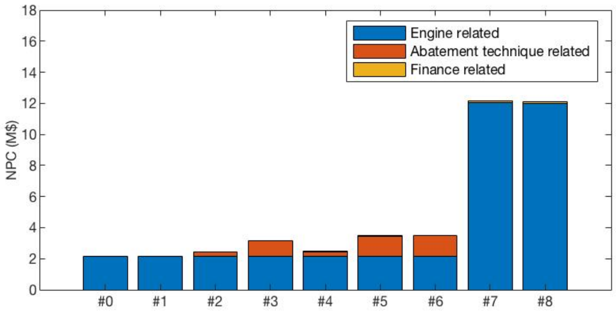


Figure 7.6: Subdivision of CAPEX

The operational expenses are given in Figure 7.7 and separated into costs related to engines, fuels and abatement techniques. Costs related to the engine are significant higher for dual-fuel and gas engines, mainly a result of the insurance costs, which are proportional with the costs of the equipment. Fuel related costs only include the lubrication costs, which have a negligible contribution. The operational expenses related to abatement techniques are the most significant for scrubbers. Scrubbers require much maintenance and consume a lot of chemicals when operating in closed loop.

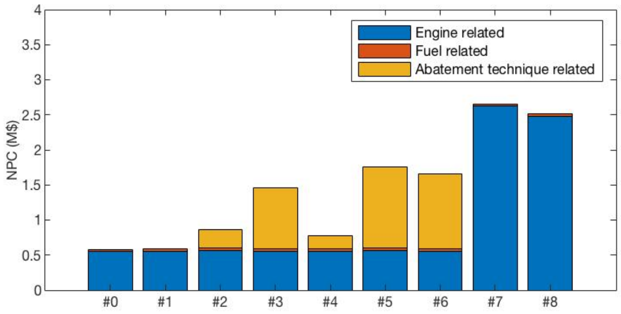


Figure 7.7: Subdivision of OPEX

The voyage expenses are given in Figure 7.8 and are separated into costs related to fuel and loss of revenue as a result of a reduction in cargo capacity required by the installation of the equipment. Port charges and carbon taxes are also voyage expenses, which have been neglected in this case study. Looking to the figure, it can be concluded that the loss of revenue for abatement techniques is very minor and negligible. The loss of revenue as a result of the volume required by LNG storage tanks is more than 8 M$ in total. Differences in fuel costs are mainly a result of different fuel prices and lower heating values. Other differences are dedicated to a difference in specific fuel consumption between the engines and fuel penalties caused by abatement techniques.

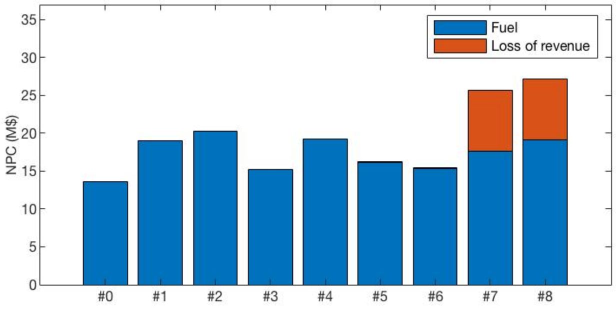


Figure 7.8: Subdivision of voyage expenses

7.4. Sensitivity analysis

To verify the influence of uncertain or variable parameters, a sensitivity analysis is conducted. A number of parameter variations have been applied to verify their influence on the total life-cycle costs of the different compliance options. The following parameter variations have been conducted:

- Variation of the discount rate.
- Variation of the finance costs.
- Variation of the scrubber price.
- Variation of the prices of the low sulphur fuels.
- Variation of the LNG price.
- Variation of the LNG tank costs.
- Variation of the loss of revenue.
- A combination of a variation of the low sulphur oil price and the LNG price.

Discount rate

When it comes to the NPV analysis, the choice of discount rate can dramatically change the evaluation. When increasing the discount rate, future costs are more discounted and high investments done at the start of the project are earned back less quickly. On the other hand, when decreasing the discount rate, future costs are less discounted and less savings during the lifetime of the ship are needed to make the compliance option with high initial investments feasible. Figure 7.9 shows the influence of varying the discount rate. The variation of the discount rate will not change the outcome significantly. The NPC of option 8 compared to option 1 at a discount rate of 0% is 67% higher. Considering a discount rate of 10%, the relative spread is increased to 97%. The conclusion is that the discount rate does certainly have influence on the results. However, the influence is in this case study not so significant that one option will be more favourable compared to another.

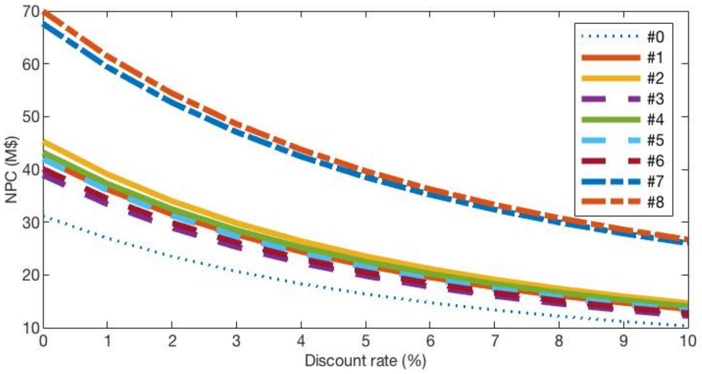


Figure 7.9: Sensitivity analysis on discount rate

Finance costs

With 70% senior debt and 10% seller's credit, the ship considered in this case study is highly leveraged. The way of financing has its effects on the results of the business case. It has already become clear in the evaluation of the results of this case study that this way of financing results in a negative value of the NPC, because the discount rate is higher than the costs of financing the project. Table 7.23 gives the benefit on the NPC in this case study compared to the case where only equity is used for financing. Obviously, the benefit is more significant for larger investments. Figure 7.10 gives the results of varying the interest rate of senior debt. For convenience, the seller's credit is kept unchanged in this sensitivity analysis. Because seller's credit takes usually not a very large share of the total amount, the effects of this financing type are not so significant as for senior debt. A 2% variation of the interest rate leads to an increase in financing costs of more than 0.7 M$ for option 7 and 8.

Table 7.23: Benefits of financing

#	*Financing NPC benefit*
0	17,777 $
1	17,777 $
2	20,154 $
3	26,139 $
4	20,389 $
5	28,515 $
6	28,750 $
7	100,032 $
8	99,615 $

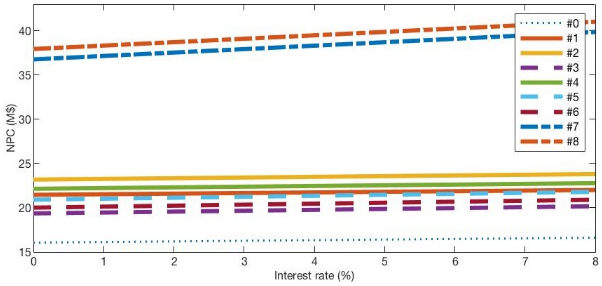


Figure 7.10: Sensitivity analysis on interest rate

Scrubber price

Many speculations are ongoing about the scrubber price. One scenario is that the price of a scrubber will rise due to an increase in popularity after 2020. When this option turns out to be lucrative, more shipowners might opt for scrubbers and due to the supply-demand mechanism, the price might rise. A counter scenario is that the price of a scrubber might drop. Scrubber manufacturers might encounter significant research & development costs, as well significant purchase costs of equipment to be able to manufacture a scrubber. Around 2020, already a notable amount of scrubbers is installed and the majority of the investment costs are payed back. This might cause a drop of the scrubber price. Table 7.24 gives the payback times of a scrubber for a variation in the scrubber price. As the scrubber price only influences the initial costs, the NPC evaluation will change proportional with the real price change.

Table 7.24: Sensitivity analysis on the scrubber price

Price change	*Nominal payback time*	*Discounted payback time*
-40%	2.4 years	2.6 years
-20%	3.2 years	3.5 years
0%	4.0 years	4.5 years
+20%	4.8 years	5.5 years
+40%	5.5 years	6.5 years

Low sulphur oil price

The success of the business case of scrubbers is largely dependent on the spread between HSFO and low sulphur fuels. Figure 7.11 gives the results of the sensitivity analysis on the prices of low sulphur fuels. The HSFO and LNG prices are kept unchanged. There can be concluded from the figure that the scrubber is in favour down to a 16% drop of the low sulphur oil prices. It is noteworthy that even the life-cycle costs of a dual-fuel engine are affected when the low sulphur fuels drop more than 10%. In this case, it is cheaper to operate on VLSGO/FO outside SECAs instead of keep using LNG. Inside SECAs, it is still favourable to operate on LNG.

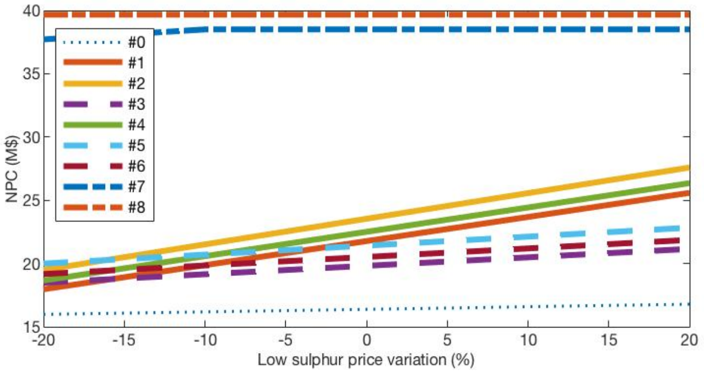


Figure 7.11: Sensitivity analysis on the low sulphur oil price

Table 7.25 gives the influences of the low sulphur oil price on the payback time of the scrubber, which shows a drastic increase of the payback time when the price of low sulphur fuels drops below the reference case.

Table 7.25: Influence on scrubber payback time

LS change	*Nominal payback time*	*Discounted payback time*
-20%	>30 years	>30 years
-10%	6.7 years	8.1 years
0%	4.0 years	4.5 years
+10%	2.8 years	3.1 years
+20%	2.2 years	2.4 years

LNG price

The results of the NPV analysis on dual-fuel and gas engines are largely dependent on the spread between LNG and oils. Figure 7.12 gives the results of the sensitivity analysis on the LNG price. Only options 7 and 8 are affected by the price change. Option 2 is the most expensive business case after options 7 and 8 and is given as reference. The conclusion that can be drawn from this graph is that a drop of the LNG price only is not enough to make this business case favourable, which might be caused by high supply costs. The supply costs of LNG that are taken into account in this case study amounts 25 to 35% of the total LNG costs.

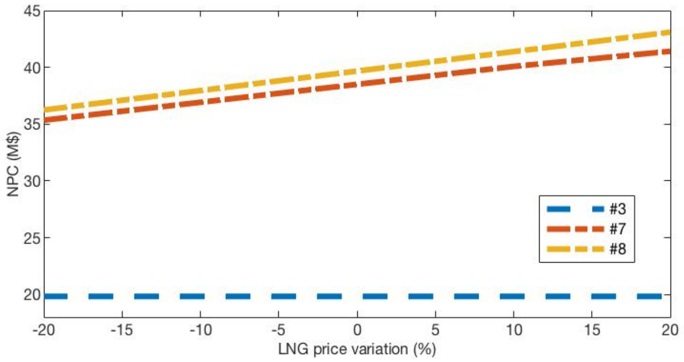


Figure 7.12: Sensitivity analysis on the LNG price

Specific gas tank costs

The specific gas tank costs take a significant share of the total capital expenses. The most expensive tank option is the use of 40 feet containerized gas tanks, which cost 300.000 $/unit and has a capacity of 35 m^3 [22]. This will be the upper limit of the sensitivity analysis. Figure 7.13 gives the results of lowering the specific gas tank costs. Option 2 is given as reference, which has the most expensive business case after options 7 and 8. A lowering of the specific gas tank costs results in a reduction of up to several millions. However, lowering the specific gas tank costs to 4000 $/$m^3$ does still not make the business case for dual-fuel and gas engines more cost effective than other compliance options.

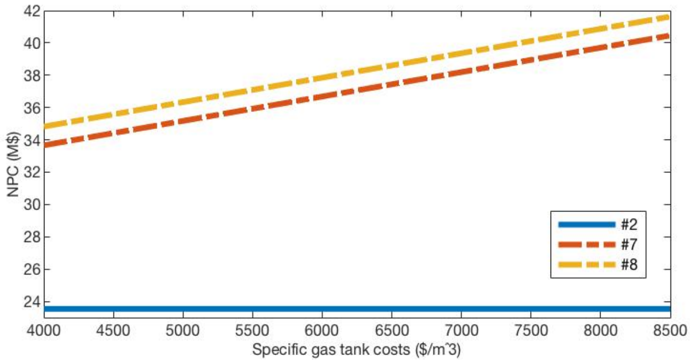


Figure 7.13: Sensitivity analysis on specific gas tank costs

Loss of revenue

In the evaluation of the results, there has been seen that the loss of revenue is relative high for the options where either a dual-fuel engine or a gas engine is installed. Due to the space required by the gas storage tanks, 14.5% of the cargo capacity is lost. The amount of cargo capacity that is lost depend however on the tank type and to what extent the tanks can be integrated in the ship design. For example, tanks that are able to fit in container slots require more space than membrane tanks fit underneath the accommodation and do not interfere the cargo capacity at all. In this case study, the net required LNG capacity is considered as loss of cargo capacity, which is the case for a membrane tank placed in the cargo holds. The results of varying the loss of revenue are given in Figure 7.14. The case where no loss of revenue is applied is most optimistic. However, even in this case, the total life-cycle costs are exceeding the costs of every other compliance option. Neglecting the loss of revenue is realistic when reviewing the entire ship design and integrating the tanks. Option 2 is given as reference, which is the most expensive business case after options 7 and 8.

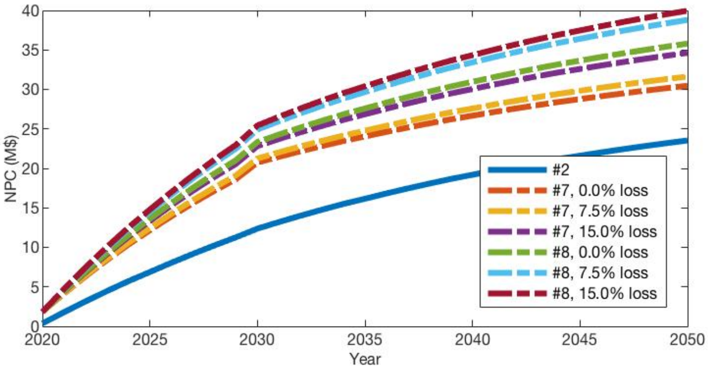


Figure 7.14: Sensitivity analysis on loss of revenue

Combination of the low sulphur oil price variation and the LNG price variation

The fuel prices appeared to have a significant influence on the final result. In this sensitivity analysis, the results of a combination of parameter variations will be shown. The first combination is given in Figure 7.15, where the low sulphur oil price and the LNG price are proportional varied. In principle, there is no interaction between both price variations, as the options using Diesel engines will burn oils and the options using dual-fuel engines and gas engines will burn LNG. Therefore, this combination of parameter variations is just an addition of the individual effects of both parameters.

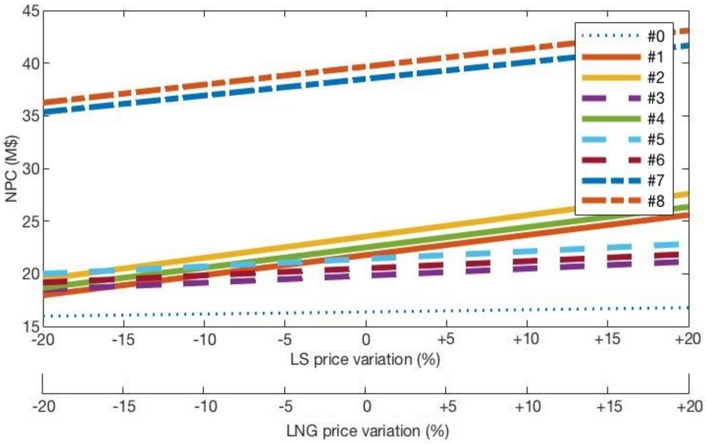


Figure 7.15: Proportional relationship between low sulphur oil price and LNG price

The second combination of parameter variations is given in Figure 7.16, where the low sulphur oil price and LNG price are inversely proportional varied. Obviously, the options with a Diesel engine installed are only affected by the low sulphur oil price variation and the option where a gas engine is installed is only affected by the LNG price. On the other hand, the evaluation of compliance option #7, with a dual-fuel engine installed, is effected by both parameter variations. Figure 7.16 shows that the dual-fuel engine is far from beneficial. However, it shows that if the LNG price will rise with more than 10% and the low sulphur oil price drops with more than 10%, the NPC evaluation drops because the engine can use oil instead of LNG. This flexibility limits the risk of the fuel price, as there can always be opted for the cheapest fuel. A disadvantage when using oil in a dual-fuel engine from the investment point of view, is that the additional CAPEX will not be payed back.

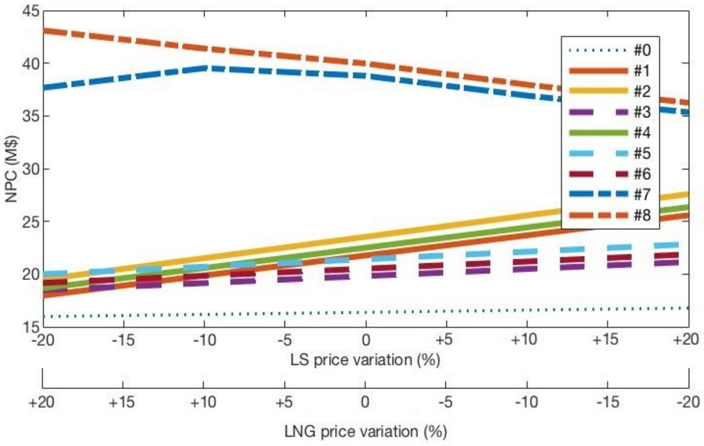


Figure 7.16: Inversely proportional relationship between low sulphur oil price and LNG price

7.5. Conclusion

A relatively small vessel is discussed in the first case study, a freezer vessel with 310,000 cbft cargo capacity and 5825 kW installed power. The freezer has a peculiar operational profile, with two-thirds of the time spent in port. After a cost & data analysis to obtain representative input values, the results are generated. The results evaluate that the installation of scrubbers is the optimal strategy for compliance with the sulphur regulations and NO_x Tier II. A scrubber has a nominal payback time of 4.0 years. The discounted payback time, taking into account a discount rate of 5%, is 4.5 years. The total life-cycle costs are reduced with 9% compared to no scrubber installation. In the calculation of these figures, the scrubber lifetime is limited to 15 years. If Tier III compliance is desired, the installation of a SCR system is the most cost effective option. The other option for a Diesel engine is the installation of an EGR system which has the main disadvantage of a fuel consumption penalty up to 7%. Substitution of Diesel engines for either dual-fuel engines or gas engines to meet both the 2020 SO_x regulations and NO_x Tier III regulations is found to be not lucrative. The intensive capital that is required, in combination with loss of revenue will make this business case not feasible.

The sensitivity analysis gave insight in the robustness of the results and the influences of parameter variations. None of the parameter variations did result in a significant change of the outcome, in the sense that it changed the preference of one compliance option over another. Some parameter variations resulted in significant changes of the discounted costs. The price of low sulphur fuels shows a very strong influence on the discounted costs of the options using low sulphur fuels. Also the payback time of scrubbers is largely influenced by this price. If the spread between low sulphur fuels drops with 10%, the payback time of a scrubber is increased by 2.7 years. The options using LNG have shown large influences by the parameter variations, especially caused by variations of the LNG price, specific gas tank costs and loss of revenue. Even though it does not make the use of LNG beneficial, large sensitivity is observed when varying those parameters. The flexibility to change fuel when having a dual-fuel engine installed, limits the risk as a result of fluctuations between the oil and gas spread.

8

Case study 2: Colour class

The containership with additional reefer capacity that will be discussed in this case is still in the design phase. Four ships of this ship type are already delivered and two are under construction. For the second generation of those containerships, the emission compliance options are still under consideration. All equipment will be installed during newbuilding. This means that the options for a later installation of abatement techniques is not considered. This case study will be used to get insight in the results for a different ship type. Compared to the first case study, an entirely different ship type and operational profile is considered. However, the cost & data analysis from Chapter 7.2 will be also considered in this case study, as this analysis is independent from the ship type and operational profile. This chapter consists of a case description, followed by the results and a sensitivity analysis. In appendices F till H, an elaboration on the input data, results and sensitivity analysis is given.

8.1. Case description

The ship that will be considered in this case is a geared specialized reefer containership. The containership with a capacity of 2256 TEU has 672 reefer plugs. In addition, the vessel is fitted with a cooling water system for the reefer containers and a remote reefer monitoring system. A picture of the Seatrade Orange, the first delivered ship of the Colour Class is given in Figure 8.1. The ship has a length over all of 185.0 metres and a summer draft of 10.0 metres. The intended commercial lifetime of the ship is 25 years.

Figure 8.1: Seatrade Orange

With the propulsion power requirement of 13100 kW, 19.6 knots should be obtained at MCR, taken into account a sea margin of 15%. As specified in the building specifications, this speed is based on the vessel design with a fixed pitch propeller, clean hull in deep water, no currents, no waves. The installed electric power requirement is 6600 kW. Due to space requirements and redundancy, this power requirement should be distributed over 4 power generators. The electric power demand varies per voyage and is dominated by the amount of reefer containers onboard.

Table 8.1 gives the engine load data that is used is this case study. The engine load data at sea is derived from the fuel consumption data of the four Colour class vessels that are already delivered and is based on figures from 2017. The container load of 1010 kW equals the operation of 404 reefer containers with an average of 2.5 kW per container. The hotel load in port turns out to be lower than at sea due to the disabling of the auxiliary systems of the main engine such as the seawater pumps and lubrication pumps. On average, the container load is assumed to be the same. Operation of the cranes is not accounted because in most ports, gantry cranes are used for cargo operations.

Table 8.1: Average auxiliary engine power

	Hotel load	***Container load***	***Total load***
Sea	430 kW	1010 kW	1440 kW
Port	360 kW	1010 kW	1370 kW

The options for emission compliance will be limited in this case study to the engines, fuels and abatement techniques that are listed in Table 8.2. Fuel cells in combination with hydrogen will not be considered because the development of this technique is not yet there. The concept is proven in practice but not all technical challenges are covered, for example the large volumes that are required for storage. Biofuels are also not considered in this case study. Biofuels are currently more expensive than conventional fuels and can be used in the future as a replacement of those fuels. However, they do not contribute to compliance with the regulations and do not add more value to the analysis if they are taken into account. The WHRS is not taken into account in the analysis because this abatement technique is only considered profitable for large power requirements above 25 MW. Since the containership that will be considered in this case study has less power requirements, the WHRS is exempted by technical constraints.

Table 8.2: Considered compliance options

Engines	***Fuels***	***Abatement Techniques***
Diesel Engine	HFSO	EGR
Dual Fuel Engine	ULSFO / GO	Scrubber
Gas Engine	VLSFO / GO	SCR
	LNG	

The first generation of Colour class vessels was intended to be used in a vessel-sharing agreement between Seatrade and CMA CGM on the worldwide Meridian service. However, after a short period of operation, the agreement has been restructured and currently, the Colour class ships are in time-charter for CMA CGM on the same service. Lately, the service has been subject to many changes in the ports of call and duration of the rotation. A typically voyage of the service is given in Table 8.3. Due to the operational profile of the ship and economic considerations, the selection of a fixed pitch propeller and directly mounted shaft to the main engine is already decided.

Table 8.3: Voyage schedule

#	***Port***	***Total distance***	***Distance SECA***	***Arrival (GMT)***	***Departure (GMT)***
1	Rotterdam (Netherlands)	-	-	01-Jan 08:00	01-Jan 21:00
2	Dunkirk (France)	105 nm	105 nm	02-Jan 03:00	02-Jan 20:00
3	Radicatel (France)	168 nm	168 nm	03-Jan 12:00	04-Jan 07:00
4	Papeete (French Polynesia)	9158 nm	258 nm	29-Jan 12:00	25-Feb 04:00
5	Noumea (New Caledonia)	2510 nm	0 nm	05-Feb 23:00	06-Feb 18:30
6	Nelson (New Zealand)	1221 nm	0 nm	10-Feb 20:00	11-Feb 12:00
7	Napier (New Zealand)	319 nm	0 nm	12-Feb 18:00	13-Feb 12:30
8	Tauranga (New Zealand)	284 nm	0 nm	14-Feb 13:00	15-Feb 09:30
9	Pisco (Peru)	5734 nm	0 nm	01-Mar 20:00	02-Mar 15:00
10	Paita (Peru)	629 nm	0 nm	04-Mar 04:00	04-Mar 23:00
11	Philadelphia (USA)	2841 nm	523 nm	15-Mar 17:00	07-Mar 08:00
12	Zeebrugge (Belgium)	3439 nm	1759 nm	24-Mar 12:00	17-Mar 04:00
13	Tilbury (UK)	120 nm	120 nm	24-Mar 13:00	25-Mar 06:00
14	Rotterdam (Netherlands)	161 nm	161 nm	25-Mar 21:00	26-Mar 08:00

Reduction on port charges is neglected in this case study. The discount that may be obtained in ports by having a high Environmental Ship Index (ESI) is very uncertain and is often retroactively defined.

8.2. Results

In the analysis, 8 compliance options are considered, as shown in Table 8.4. The ship will become operational in 2021 and will operate worldwide, both in the United States' NECA and the European NECA. Therefore, it needs to comply with Tier III NO_x limits. As indicated in Table 8.4, compliance option 1 and 3 are not complying with the Tier III limits. However, the results of those options are also given. Compliance options 1 and 3 are useful to get insight in the influences of the installation of a scrubber on it's own. In addition to the 8 compliance options, a benchmark is given which represents the situation as it was before 2020, using high sulphur fuels outside SECAs and using ultra low sulphur fuels inside SECAs. This benchmark is given in order to be able to assess the change in costs as a result of the 2020 sulphur cap.

Table 8.4: Considered options & compliance

#	*Engine*	*Abatement Techniques*	*Tier III compliance*	*SO_x compliance > 2020*
0	Diesel Engine	-	No	No
1	Diesel Engine	-	No	Yes
2	Diesel Engine	EGR	Yes	Yes
3	Diesel Engine	Scrubber	No	Yes
4	Diesel Engine	SCR	Yes	Yes
5	Diesel Engine	EGR + Scrubber	Yes	Yes
6	Diesel Engine	Scrubber + SCR	Yes	Yes
7	Dual Fuel Engine	-	Yes	Yes
8	Gas Engine	-	Yes	Yes

With the given voyage schedule, the operational profile of the ship can be determined. This operational profile is the same for all alternatives, except for the alternative using LNG as fuel. For this alternative, the port time is accounted because no bunker operations are allowed simultaneously with cargo operations. The general operational profile, where there is not accounted for additional bunker time, is given in Figures 8.2 and 8.3. Figure 8.2 shows the part of the time that the ship is in port, sailing inside SECAs and sailing outside SECAs. Containerships are especially designed for short port calls, this is reflected in the operation profile. Where the Freezer vessel from the first case study spent 69% of the time in port, the Colour class in this case study spent only 13% of the time in port. Only 12% of the sailing time is spent in SECAs.

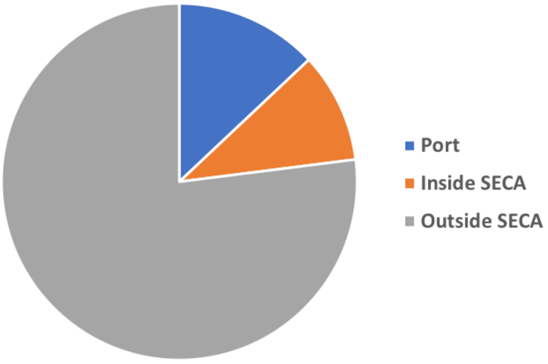


Figure 8.2: Relative time profile

The absolute time spent in the different areas is given in Figure 8.3. The required service speeds are determined by the fixed port slots of every call. Due to the fixed port slots, a variable speed profile is seen from 10.5 to 17.5 knots. One single roundtrip will last 12 weeks and has an average speed of 15.2 knots. In the determination of the time spent in port, 20% of additional port time is accounted for some possible delay, waiting time and mooring/unmooring.

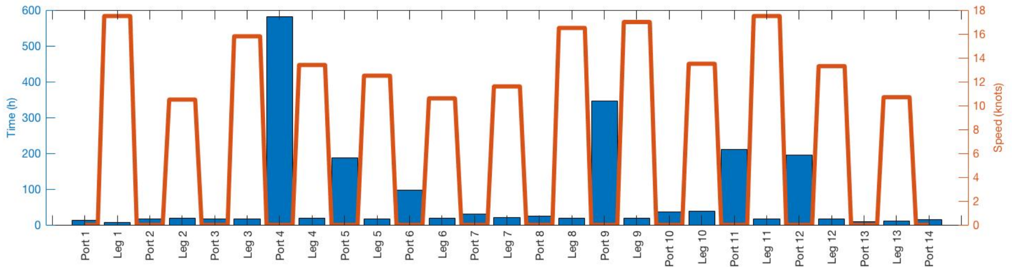


Figure 8.3: Operational profile, time and speed

The total energy demand per voyage is 14,226 MWh, if no power correction factor is applied for the installation of abatement techniques and no additional bunker time is accounted. Taking into account the specific fuel consumption and the lower heating value of LNG (49.2 MJ/kg), the total energy demand equals a LNG consumption of 2131 T. The required endurance as stated in the building specifications is 15,000 nm, what comes down to about half a roundtrip. Therefore, a LNG consumption of 1066 T will be taken into account for the calculation of the tank capacity. With an average volumetric density of 450 kg/m^3, the corresponding LNG volume is 2368 m^3. In order to obtain the required tank size, 5% engine consumption margin, 15% safety buffer and 85% tank utilization are used, in line with the assumptions of Balland [9]. Taking those assumptions into account, the required tank size is 3343 m^3. The only ports in the schedule where bunkering of LNG is possible are Rotterdam and Zeebrugge [32]. Therefore, it is currently impossible to bunker LNG twice a roundtrip. However, for this case study, there will be assumed that it is possible to bunker twice a roundtrip. Bunkering by barge is required, as the large amounts of required fuel will make bunkering by truck practically not feasible. As not everywhere simultaneous cargo operations are allowed during bunkering of LNG, 6 hours of additional port time will be accounted for each bunkering. This additional port time originates from the assumptions made in the first case study, where a bunker speed of 600 m^3/h can be obtained. The additional port time will be compensated on the ocean stretches from Radicatel to Papeete and from Tauranga to Pisco.

Table 8.5 gives for each case the fuel that is used, both inside and outside SECAs. Like in the first case study, the compliance option uses the cheapest compatible fuel in the calculation and with the set of input data that is used, low sulphur gas oils are selected for Diesel engines. The discount on low sulphur fuel oils with respect to low sulphur gas oils does not outweigh the difference in energy content per unit of mass and the additional running costs.

Table 8.5: Fuel choice for compliance options

#	***Fuel, global***	***Fuel, SECA***
0	HSFO	ULSGO
1	VLSGO	ULSGO
2	VLSGO	VLSGO
3	HSFO	HSFO
4	VLSGO	ULSGO
5	HSFO	HSFO
6	HSFO	HSFO
7	LNG	LNG
8	LNG	LNG

Figure 8.4 shows an overview of the results, a cost comparison for 25 years. The options where scrubbers are installed appeared to be the most cost effective choice, with already a positive net difference after the first operational year. The nominal payback time of a scrubber, not taking into account the financing and the time value of money, is 2.2 years. The discounted payback time is 2.4 years. The options using LNG are clearly separated from the options using oils, they are never beneficial compared to the conventional Diesel engine in this case study.

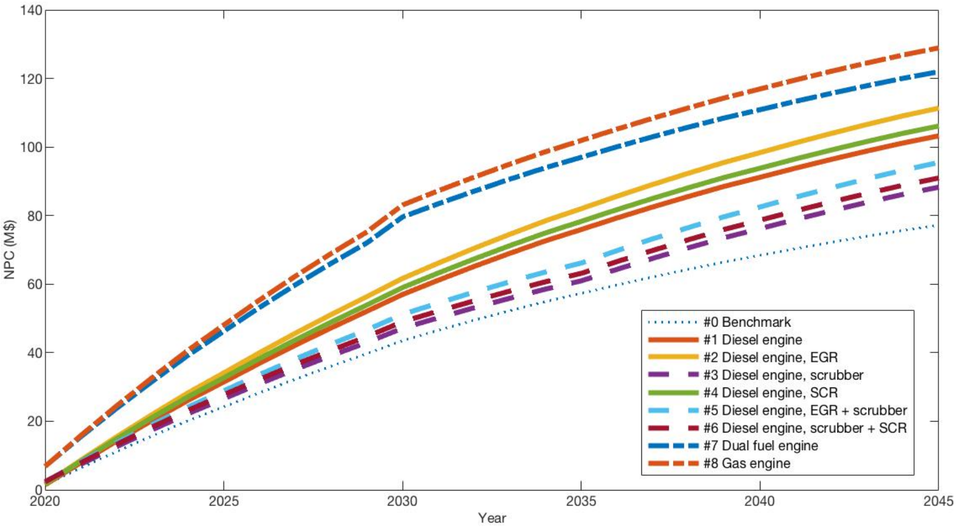


Figure 8.4: Total life-cycle costs

Table 8.6 gives the final results of the total life-cycle costs, taken into account a discount rate for the NPV analysis of 5%. Figure 8.5 gives a breakdown of those costs into the categories CAPEX, OPEX and voyage expenses. The largest CAPEX are seen in option 7 and 8, where a large amount of expensive gas storage tanks are required. The investments in NO_x reduction techniques result in additional investment costs, but does not lead to a reduction of running cost, something that a scrubber certainly does. The results are very comparable to the first case study, but on a significant higher cost level.

Table 8.6: Total life-cycle costs

#	***Total life-cycle costs***
0	77.21 M$
1	103.27 M$
2	111.35 M$
3	88.32 M$
4	106.14 M$
5	95.52 M$
6	91.00 M$
7	121.97 M$
8	128.93 M$

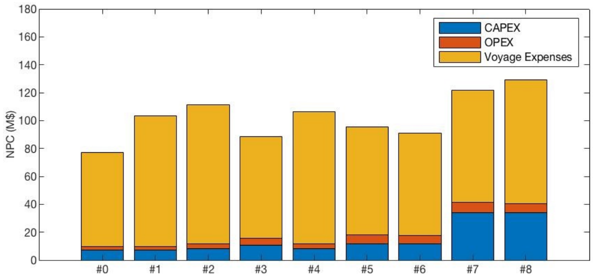


Figure 8.5: Subdivision of life-cycle costs

The capital expenses are given in Figure 8.6 and separated into costs related to engines, abatement techniques and financing. The discount rate is higher than the average finance costs, therefore the discounted finance costs are negative and deducted from the total capital costs. In the sensitivity analysis of the first case study, it became clear that making use of financing methods other than equity results in a reduction of the total NPC of up to 0.2%.

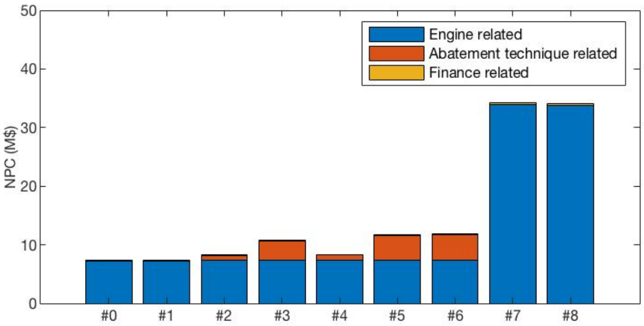


Figure 8.6: Subdivision of CAPEX

The operational expenses are given in Figure 8.7 and are separated into costs related to engines, fuels and abatement techniques. Similar to the first case study, fuel related OPEX are very comparable and minor for the different options. The main difference is seen in the OPEX related to engines and abatement techniques. The difference in OPEX for engines is mainly due to the insurance costs, whose are proportional to the value of the equipment. The most contributing cost item related to a scrubber, the abatement technique with the largest OPEX, is the additional engineer that is placed for operating the scrubber and do maintenance on the scrubber.

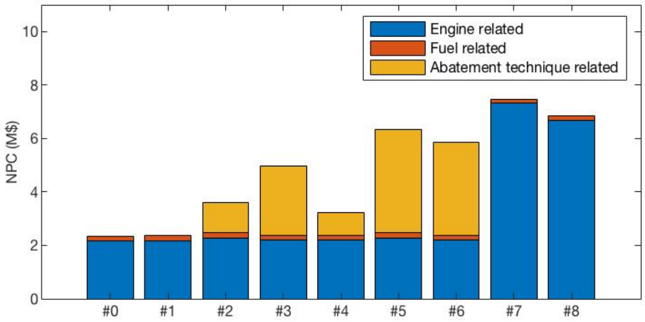


Figure 8.7: Subdivision of OPEX

The voyage expenses are given in Figure 8.8 and are separated into costs related to fuels and loss of revenue. The latter is a result of a reduction in cargo capacity required by the installation of the equipment. However, the loss of revenue in this case study is minor and not so significant as it was for the first case study. Other voyage expenses (port charges and carbon taxes) have been neglected. The reduction on port charges by being environmental friendly is very uncertain and often retroactively defined. Carbon taxes are not yet enforced, but might be in the future.

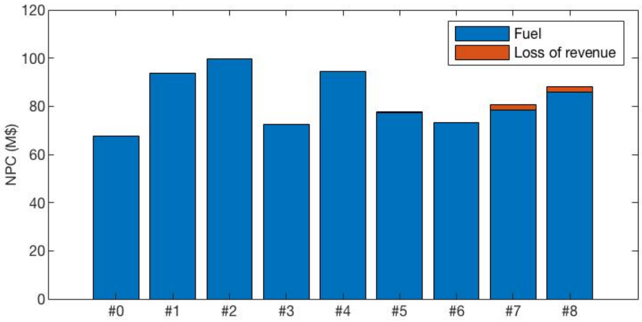


Figure 8.8: Subdivision of voyage expenses

8.3. Sensitivity analysis

To verify the influence of uncertain or variable parameters, a sensitivity analysis is conducted. A number of parameter variations have been applied to verify their influence on the total life-cycle costs of the different compliance options. The following parameter variations have been conducted:

- Variation of the scrubber price.
- Variation of the prices of the low sulphur fuels.
- Variation of the LNG price.
- Variation of the LNG tank costs.
- Variation of the voyage duration.
- A combination of a variation of the LNG price and a variation of the LNG tank costs.

The variation on the discount rate and finance costs had limited influence on the results of the first case study and will not be considered again in the sensitivity analysis of this case study. Variation of the loss of revenue did have reasonable influence on the compliance options that used LNG as a fuel in the first case study. However, the loss of revenue in this case study takes only 3% share of the discounted voyage expenses, while for the first case study this was 19%. Therefore, a variation of the loss of revenue will not be discussed in this case study. In addition to the first case study, a variation of the voyage duration will be applied.

Scrubber price

Similar to the first case study, the influences of a variation of the scrubber price on the payback time of the scrubber is considered. The payback times of the scrubber, corresponding to the parameter variations, are given in Table 8.7. Results show that the differences between the nominal payback time and the discounted payback time are limited and do not affect the results of the investment decision. It shows also that a variation of the scrubber price results in an increased or decreased payback time of a few months.

Table 8.7: Influence of the scrubber price on scrubber payback time

Price change	*Nominal payback time*	*Discounted payback time*
-40%	1.3 years	1.4 years
-20%	1.8 years	1.8 years
0%	2.2 years	2.4 years
+20%	2.6 years	2.9 years
+40%	3.0 years	3.3 years

Low sulphur oil price

The spread between HSFO and low sulphur fuels will make or brake the business case of scrubbers. Figure 8.9 gives the results of the sensitivity analysis on the prices of low sulphur fuels. The HSFO and LNG prices are kept unchanged. There can be concluded that up to a 20% drop of the low sulphur oil price, the scrubbers will always be in favour. Similar to the first case study, the dual-fuel engine will operate on ULSGO/FO outside SECAs instead of keep using LNG. Inside SECAs, it is still favourable to operate on LNG.

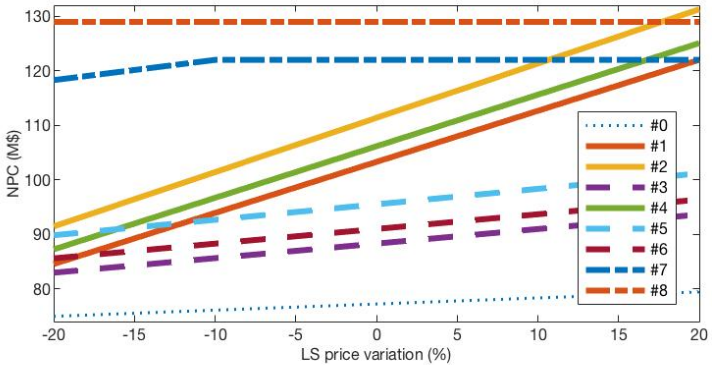


Figure 8.9: Sensitivity analysis on the low sulphur oil price

Table 8.8 gives the influences of the low sulphur oil price on the payback time of the scrubber, which shows a drastic increase of the payback time when the prices of low sulphur fuels drop below the reference case. There can be concluded that the low sulphur oil price is a key parameter with respect to the scrubber payback time.

Table 8.8: Influence of the LS price on the scrubber payback time

LS change	*Nominal payback time*	*Discounted payback time*
-20%	7.6 years	9.6 years
-10%	3.4 years	3.8 years
0%	2.2 years	2.4 years
+10%	1.6 years	1.7 years
+20%	1.3 years	1.4 years

LNG price

The results of the NPV analysis on dual-fuel and gas engines depend largely on the spread between LNG and oils. Figure 8.10 gives the results of the sensitivity analysis on the LNG price. Only options 7 and 8 are affected by the price change. A 20% LNG price variation results in a variation of the NPC evaluation of up to 13%. The conclusion that can be drawn from this graph is that dual-fuel engines only become favourable for Tier III compliance at a reduction of the LNG price of more than 20%.

At a 20% drop of the LNG price, the dual-fuel option end up with about the same NPC as the scrubber case in combination with SCR systems. In that situation, the nominal payback time of a dual-fuel installation is 14.7 years. However, the discounted payback time exceeds the operational lifetime of the ship. For gas engines, the results are less competitive with the other compliance options, mainly due to the fact that no two stroke gas engines are available and therefore the specific fuel consumption for main engines than for dual-fuel engines.

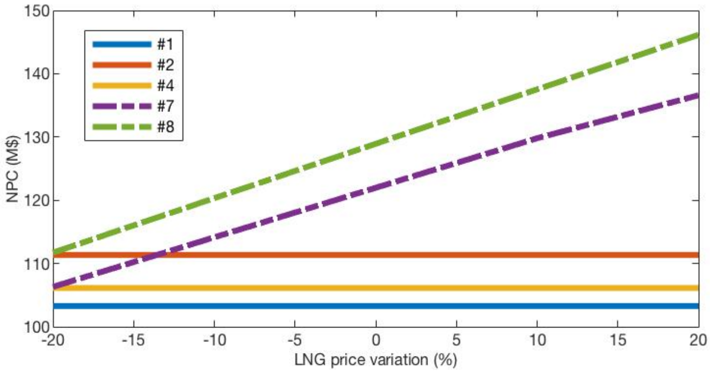


Figure 8.10: Sensitivity analysis on the LNG price

LNG tank costs

The total capital expenses are largely influenced by the expensive gas tanks. Figure 8.11 gives the results of the sensitivity analysis on the LNG price. The upper bound of the sensitivity analysis represents the use of 40 feet containerized tanks. The conclusion than can be drawn from this graph is that the economics of dual-fuel engines and gas engines are largely influenced by the specific gas tank costs. Within the limits of this sensitivity analysis, the results have a variation of 17.7 M$. Obviously, a lowering of the specific gas tank costs will make the business case for LNG much more attractive. When the specific gas tank costs are 4000$, the nominal payback time of a dual-fuel system is 18.3 years. The discounted payback time exceeds the lifetime of the ship.

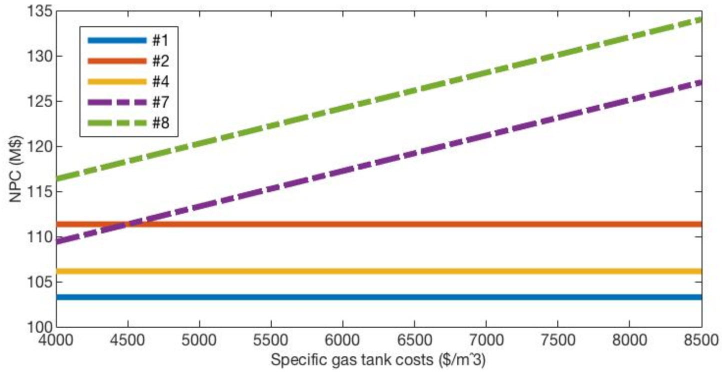


Figure 8.11: Sensitivity analysis on the specific gas tank costs

Voyage duration

The voyage duration used in this case study is 12 weeks. In this sensitivity analysis, the effects of increasing and decreasing the voyage duration with 1 week are captured. The duration and number of the port calls within one roundtrip are in all cases kept the same. Basically, a decrease of the voyage duration to 11 weeks means that in one year, almost half a roundtrip more can be covered. Table 8.9 shows the effects of the variation of the voyage duration on the total life-cycle costs of the compliance option #1 (Diesel engine without abatement techniques) and the compliance option #3 (Diesel engine + scrubber). Also, the influence on the payback time of a scrubber is given. It is trivial that if the voyage duration drops, the payback time of the scrubber decreases. A drop of the voyage duration causes the required ship speed to rise and as a consequence, also the fuel consumption will rise. This amplifies the advantage of being able to burn HSFO.

Table 8.9: Sensitivity analysis on the voyage duration, scrubbers

Voyage duration	*NPC #1*	*NPC #3*	*Nominal payback time*	*Discounted payback time*
11 weeks	126.97 M$	107.07 M$	1.7 years	1.8 years
12 weeks	103.27 M$	88.29 M$	2.2 years	2.4 years
13 weeks	80.76 M$	70.56 M$	2.9 years	3.2 years

Table 8.10 shows the effects of the variation of the voyage duration on the total life-cycle costs of the compliance option #4 (Diesel engine + SCR), compliance option #7 (Dual fuel engine) and compliance option #8 (Gas engine). The required gas tank capacity is also given, which has it's primary effects on the total investment costs. The secondary effects of the tank capacity are present on the bunker time and loss of revenue. However, the voyage duration does not have influence on the payback times of both the dual-fuel engines and gas engines, in the sense that the payback times changes to periods within the lifetime of the ship.

Table 8.10: Sensitivity analysis on the voyage duration, LNG

Voyage duration	*NPC #4*	*NPC #7*	*NPC #8*	*Gas tank capacity*
11 weeks	130.22 M$	147.54 M$	154.36 M$	3875 m^3
12 weeks	106.14 M$	121.97 M$	128.93 M$	3343 m^3
13 weeks	83.33 M$	100.57 M$	105.44 M$	3037 m^3

Combination of the LNG price and the LNG tank costs

As the business case for LNG appeared to be largely influenced by the LNG tank costs and especially by the price of LNG, this sensitivity analysis will focus on the combination of both parameter variations. The first combination is given in Figure 8.12, where the LNG price and the specific tank costs are proportional varied. The graph looks similar to Figure 8.10, where only the LNG price is varied. However, the slope of the lines of compliance options #7 and #8 are somewhat steeper, which means that both parameter variations amplify each-other to a certain extent.

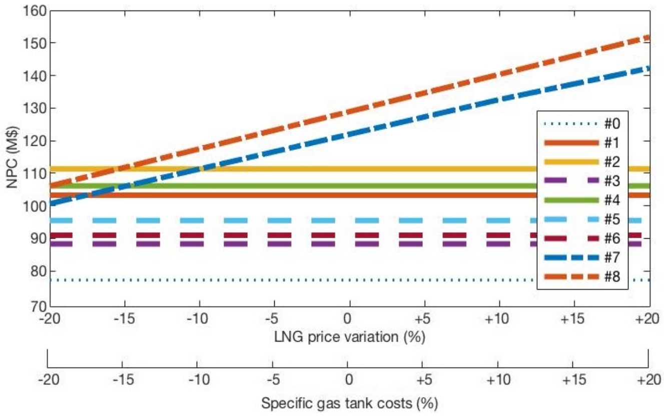


Figure 8.12: Proportional relationship between the LNG price and the LNG gas tank costs

Table 8.11 gives the influences of the proportional parameter variations on the payback times of the dual-fuel system. A discount of 20% on both the LNG price and the LNG tank costs will lead to a discounted payback time which is shorter than the lifetime of the ship. For the other cases, the discounted payback time exceeds the lifetime of the ship.

Table 8.11: Influence of the proportional relationship between the LNG price and the LNG tank costs on the dual-fuel engine payback time

LNG price	*LNG tank costs*	*Nominal payback time*	*Discounted payback time*
-20%	-20%	11.8 years	17.5 years
-10%	-10%	18.4 years	>25 years
0%	0%	>25 years	>25 years
+10%	+10%	>25 years	>25 years
+20%	+20%	>25 years	>25 years

The second combination of parameter variations is given in Figure 8.13, where the LNG price and the price of the LNG tank costs are inversely proportional varied. The slope of the line corresponding to compliance options #7 and #8 are more flat compared to Figure 8.10, where only the LNG price is varied. This means that both parameter variations compensate each other to a certain extent. However the LNG price dominates.

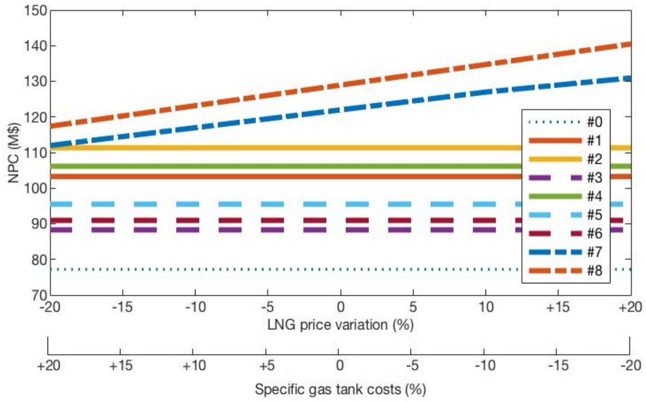


Figure 8.13: Inverse proportional relationship between the LNG price and the LNG gas tank costs

Table 8.12 gives the influences of the inverse proportional parameter variations on the payback time of the dual-fuel system. Compared to the proportional parameter variations, the payback periods will be less favourable.

Table 8.12: Influence of the inverse proportional relationship between the LNG price and the LNG tank costs on the dual-fuel engine payback time

LNG price	***LNG tank costs***	***Nominal payback time***	***Discounted payback time***
-20%	+20%	17.7 years	17.5 years
-10%	+10%	22.8 years	>25 years
0%	0%	>25 years	>25 years
+10%	-10%	>25 years	>25 years
+20%	-20%	>25 years	>25 years

8.4. Conclusion

A specialized reefer containership is discussed in this second case study with a total capacity of 2256 TEU and 672 reefer plugs. This ship has a worldwide operational profile with relative high ship speeds and short calls, which is typically for containerships. Evaluation of the results shows that the installation of scrubbers is the optimal strategy for those cases where NO_x Tier II compliance is required. A scrubber has a payback time of 2.2 years. The total life-cycle costs are reduced with 15% compared to the case without scrubber installation. In the calculation of these figures, the scrubber lifetime is limited to 15 years. Tier III compliance is desired for this ship, as she operates in both the America and the Europe NECAs. For Tier III compliance, the most cost effective option is the combination of a scrubber with a SCR unit. The scrubber does not contribute to any NO_x benefit but this combination of abatement techniques is preferred above the single installation of a SCR unit and dual-fuel engines. Compared to the first case study, the perspectives for installation of dual-fuel engines has improved, but not to an extent that this option will become attractive from an investment point of view.

The sensitivity analysis gave insight in the influence of different parameters. None of the parameters changed the advantages of scrubbers. The difference with the other compliance options and the payback time of the scrubbers is certainly affected. The biggest influence is caused by the low sulphur oil price, where a 20% drop of the spread between HSFO and low sulphur fuels causes the discounted payback time of the scrubber to drop from 2.4 years to 9.6 years. The evaluation of the results for dual-fuel engines and gas engines is changed by a number of parameters. Especially any drop of the LNG price will improve the business case of LNG. Other effects that might change the feasibility and payback time of the LNG business case are the low sulphur oil price, the specific gas tank costs and the voyage duration. A 20% reduction of both the LNG price and the specific gas tank costs results in a nominal payback time of 11.8 years for the dual-fuel system. Obviously, a shorter voyage duration requires higher ship speeds, which result in more fuel consumption and a shorter payback time of both scrubbers and LNG installations.

9

Case study 3: Baltic Klipper

The ship that will be discussed in this case study is delivered in 2010 and will be considered for retrofit. The retrofit of the engine to dual-fuel is not possible and the installation of NO_x abatement techniques is not required. Therefore, only the installation of a scrubber will be considered. A new cost & data analysis is presented, which covers all input parameters specifically related to retrofit. Next, the results of this case study are presented. The sensitivity analysis gives insight in the influences of a variation of the key parameters. In appendices I till K, an elaboration on the input data, results and sensitivity analysis is given.

9.1. Case description

The ship that will be considered in this case study is a geared specialized reefer ship with a hold capacity of 661,636 cbft, distributed over 4 holds. On deck, containers can be carried with a capacity of 503 TEU and 200 electrical reefer plugs are available. In the holds, 108 containers can be carried instead of refrigerated cargoes. However, no reefer plugs are available in the holds. A picture of the Baltic Klipper is given in Figure 9.1. The ship has a length over all of 165.0 metres and a summer draft of 10.3 metres. The Baltic Klipper has one sister-vessel, the Atlantic Klipper, which is delivered in 2011. The calculations will start from 2020, when the new sulphur limits will be enforced. However, the scrubber will be installed in the course of 2020, along with the drydock schedule. For the calculations, the retrofit is assumed to be ready at the start of 2021. The intended commercial lifetime of the ship is 30 years, of which the last 20 years will be considered in this case study.

Figure 9.1: Baltic Klipper

The service speed of the ship is 20.4 knots, which is obtained with 12852 kW (NCR) and 101 rpm at the design draft, taking into account a sea margin of 15%. The NCR is the rating at which the engine can be operated most efficiently, economically and with least maintenance [88]. The maximum speed is 21.1 knots at 14280 kW (MCR) and 105 rpm, also including 15% sea margin. The installed main engine is a Hitachi - MAN B&W 6S60MC-C. Four auxiliary engines are installed with each 1620 kW power output, from the engine manufacturer Yanmar.

The options for emission compliance that will be considered in this case study are limited to the engine, fuels and abatement techniques that are listed in Table 9.1. One big constraint in this case study, and for retrofits in general, is that the ship design is adapted to the current propulsion configuration. This means that there will be certainly a challenge to fit the new equipment in the current design. The initial configuration consists of a Diesel engine using HSFO outside SECAs and ULSFO inside SECAs. No abatement techniques are installed. To fulfill the global sulphur cap of 2020, two options can be chosen. The first, using low sulphur fuels, does not require large investments in comparison to the second option, installing a scrubber. Retrofit of the existing main engine to dual-fuel operation is not possible because of the missing electronic system, unless the engine is first retrofitted with a common rail system. However, this will be a very expensive retrofit [45]. Replacement of the main engine is also too expensive [45]. This has already been examined by GDF Suez and can also be substantiated with the previous case studies and other researches. For the previous case studies, the payback time of the dual-fuel business case exceeds the lifetime of the ship. Parsmo et al. indicate that the complete retrofit including installation is approximately 40% more expensive compared to the newbuild of a dual-fuel installation [118]. Besides that, the offhire time for such a retrofit is approximately 40 days, which drives up the costs by additional drydock costs and loss of revenue [84].

Table 9.1: Considered compliance options

Engines	***Fuels***	***Abatement Techniques***
Diesel Engine	HSFO	Scrubber
	ULSFO / GO	
	VLSFO / GO	

The ship, as it is in the current state, only complies with NO_x Tier I, which is satisfactory because the keel laying date of the ship is before 2011. If using low sulphur fuels or installing a scrubber, nothing changes to this requirement. If either retrofitting the engines to dual-fuel engines or installing new engines was considered, this would be a major conversion and more strict NO_x regulations would apply, which is Tier III when sailing in the North America and Caribbean Sea NECA. When this area is excluded from the operational profile, only Tier II compliance is required. The dual-fuel two-stroke engines from MAN B&W have high-pressure injection systems, meaning that they only have Tier II compliance. For Tier III compliance in that respect, the installation of a SCR system is required.

The Baltic Klipper and Atlantic Klipper are currently operating in the Caribanex service of Seatrade in collaboration with Geest line. The Caribanex service is a liner service with weekly sailings from the Caribbean to Europe, mainly focusing on bananas loaded under deck. On the voyage back to the Caribbean, mainly project cargo is shipped. A typically voyage of the service is given in Table 9.2. The number of ports that are called in the Caribbean are different per voyage and depend on the cargo that is available at that particular moment.

Table 9.2: Voyage schedule

#	***Port***	***Total distance***	***Distance SECA***	***Arrival (GMT)***	***Departure (GMT)***
1	Turbo (Colombia)	-	-	01-Jan 08:00	01-Jan 19:30
2	Santa Marta (Colombia)	283	0	02-Jan 11:00	03-Jan 00:30
3	Manzanillo (Dom. Republic)	644	0	04-Jan 11:30	06-Jan 09:30
4	Dover (UK)	3886	258	15-Jan 08:00	17-Jan 21:00
5	Flushing (Netherlands)	92	92	18-Jan 04:00	20-Jan 00:30
6	Le Havre (France)	193	193	20-Jan 12:30	21-Jan 03:00
7	Fort de France (Martinique)	3361	207	29-Jan 17:00	30-Jan 02:00
8	Bridgetown (Barbados)	134	0	30-Jan 13:00	31-Jan 00:00
9	St. Georges (Grenada)	162	0	31-Jan 10:00	31-Jan 19:00
10	Castries (Saint Lucia)	131	0	01-Feb 02:00	01-Feb 14:30
11	Turbo (Colombia)	1075	0	03-Feb 22:30	05-Feb 08:00

Reduction on port charges is neglected in this case study. The discount that may be obtained in ports by having a high Environmental Ship Index (ESI) is very uncertain and is often retroactively defined. That indicates that the advantage is difficult to predict but does not take away the benefit that shipping companies may have when investing in environmental friendly techniques.

The electric power demand varies per voyage and is dominated by the type of cargo and the number of reefer containers on board. Typically, on the Eastbound trade from Turbo to Flushing, bananas are loaded in the cargo holds and reefer containers are mainly loaded with a mixture of commodities, flowers and avocados. On the Westbound trade from Flushing back to Turbo, the hold reefer plant is switched off and mainly cars are transported. Also, some reefer containers are taken back to the Caribbean, but the number is significant lower than on the Eastbound trade. Figure 9.3 gives the engine load data that is used in this case study. The auxiliary engine load data at sea is derived from the reported data from the Baltic Klipper and Atlantic Klipper, an average of the entire voyage is taken. As both ships have recently entered the time-charter on the Caribanex service, limited data is available and the data that is used in this research is taken from one single voyage of both ships. The consumption of the hold reefer plant is 900 kW when loaded with bananas and 0 kW when loaded with project cargo. A weighted average is taken for the entire voyage. The container load of 187 kW equals the operation of 75 containers with an average of 2.5 kW per container. The hotel load in port turns out to be lower than at sea due to the disabling of the auxiliary systems of the main engine such as the seawater pumps and lubrication pumps. On average, the container load is assumed to be the same in port as at sea. The reefer plant consumes 640 kW in ports where refrigerated cargo is loaded. A weighted average is taken for the entire voyage, taken into account some ports where the reefer plant is disabled.

Table 9.3: Average auxiliary engine power

	Hotel load	***Reefer plant***	***Container load***	***Total load***
Sea	500 kW	425 kW	187 kW	1112 kW
Port	420 kW	370 kW	187 kW	977 kW

9.2. Cost & data analysis

In this analysis, the values that are used as input for the model are given and substantiated with previous researches, as indicated. The required input data is divided into finance related, engine related, fuel related and abatement related parameters. All costs & data that are presented in this chapter are specifically related to a retrofit project. Other costs and data are used from Chapter 7.2, this will be indicated.

Finance related

The possibility of financing newbuildings is well known. However, financing retrofit projects is no common use, at least not for such large amounts of capital involved as for retrofitting a scrubber or dual-fuel engines. One company that provides loans for retrofit projects is Clean Marine Energy, based in the Netherlands. A similar service has been offered by Export Credit Norway. The latter financing institution requires a minimum of 30% Norwegian content, because the company is owned by the Norwegian government. However, the structure and conditions of the loans are transparent and will be therefore used in this case study. Export Credit Norway can finance up to 85% of the retrofit contract value. The repayment period varies from 5 to 8.5 years. Export Credit Norway offers loans with two different sets of interest terms: fixed-rate Commercial Interest Reference Rate (CIRR) loans and market based Interbank Offered Rate (IBOR) loans with variable rates. For this case study, the CIRR of the period 15-03-2018 to 14-04-2018 is used and is 3.4%. The financial structure that is used in this case study is given in Table 9.4.

Table 9.4: Finance sources retrofit

Finance source	***Share***	***Repayment type***	***Interest rate***	***Tenor***
Owner equity	15%	-	-	-
Senior debt	85%	Yearly repayment	3.4%	8 years
Mezzanine debt	0%	-	-	-
Seller's credit	0%	-	-	-

Engine related

The costs of a Diesel engine were on average 251.0 $/kW excluding installation, as given in Chapter 7.2. These costs will be also used in the calculations of this case study. As we will not consider the installation of new Diesel engines, these costs will only be used for the calculation of the insurance costs related to the engine.

Fuel related

The fuel related input is not changed compared to the previous case studies. Therefore, the cost and data as given in Chapter 7.2 will be used.

Abatement technique related

The only abatement technique that is considered in this case study is the scrubber. According to den Boer & ’t Hoen, the additional costs that should be taken into account for retrofit will be 60 $/kW [27]. When using the prices of a scrubber from Chapter 7.2, this comes down to a total of 234.5 $/kW. Balland indicates that the yard costs may vary significantly, which is caused by the fluctuating market conditions [9]. The operational weight of a hybrid scrubber of 20.8 MW will be 37.4 T. The offhire time that is required for installing a scrubber is 20 days, which is less than the drydock period [84]. That means that no additional drydock costs and offhire time will be taken into account when planning the installation during a scheduled drydock period.

9.3. Results

In this analysis, 2 compliance options are considered, as shown in Table 9.5. Compliance option 1 uses low sulphur fuels. Compliance option 2 uses high sulphur fuel, which is allowed by installing a scrubber. In addition, a benchmark is given which represents the situation as it was before 2020, using high sulphur fuels outside SECAs and using ultra low sulphur fuels inside SECAs. This benchmark is given in order to be able to assess the costs change as a result of the 2020 sulphur cap.

Table 9.5: Considered options & compliance

#	*Engine*	*Abatement Techniques*	*Tier III compliance*	*SOx compliance >2020*
0	Diesel Engine	-	No	No
1	Diesel Engine	-	No	Yes
2	Diesel Engine	Scrubber	No	Yes

With the given voyage schedule, the operational profile of the ship can be determined. The operational profile is the same for all alternatives. Figure 9.2 shows the part of the time that the ship is in port, sailing inside SECAs and outside SECAs. Reeferships are designed to sail at fast speeds but loading takes some time. This is reflected in the operational profile, the ship spent 42% of the time in port. A limited percentage of 5% of the time is spent in SECAs.

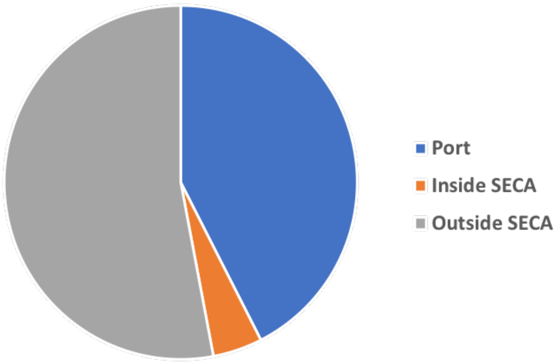


Figure 9.2: Relative time profile

The absolute time spent in the different areas is given in Figure 9.3. The required service speeds are determined by the fixed port slots of every call. Due to the fixed port slots, a variable speed profile is seen from 12.2 to 19.2 knots. One single roundtrip will last 5 weeks and has an average sailing speed of 17.4 knots. The sailing time consists of the sea stretches. Time spent from the pilot area to the berth is included in the port times.

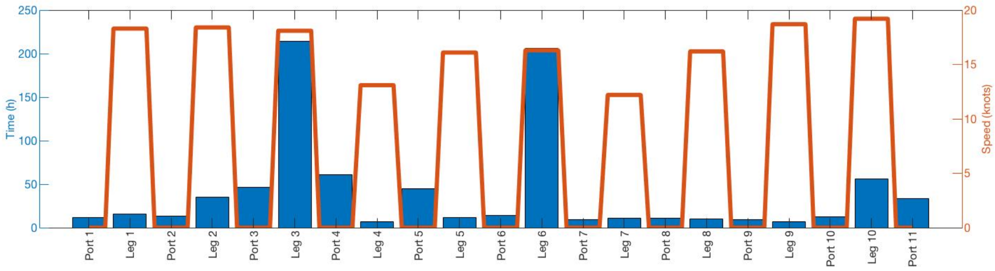


Figure 9.3: Operational profile, time and speed

Table 9.6 gives for each case the fuel that is used, both inside and outside SECAs. Like in the previous case studies, the compliance options use the cheapest compatible fuel in the calculation and with the set of input data that is used, low sulphur gas oils are selected. The discount on the low sulphur fuel oils with respect to low sulphur gas oils does not outweigh the difference in energy content per unit of mass and the additional running costs.

Table 9.6: Fuel choice for compliance options

#	***Fuel, global***	***Fuel, SECA***
0	HSFO	ULSGO
1	VLSGO	ULSGO
2	HSFO	HSFO

Figure 9.4 shows an overview of the results, a cost comparison for 20 years. The compliance option with a scrubber installed appeared to be the most cost effective choice, with already a positive net difference after the first operational year. However, this option will not be more beneficial than the benchmark. The reason is that the operational profile covers a very small percentage of time inside SECAs, the only area where compliance option 1 has an advantage with respect to the benchmark. This minor advantage of voyage expenses will not compensate the additional CAPEX and OPEX as a result of installing and operating the scrubber. The discounted payback time of a scrubber, calculated with a discount rate of 5% and without financing, is 4.1 years. The nominal payback time of a scrubber, calculated with a discount rate of 0% and without financing, is 3.7 years.

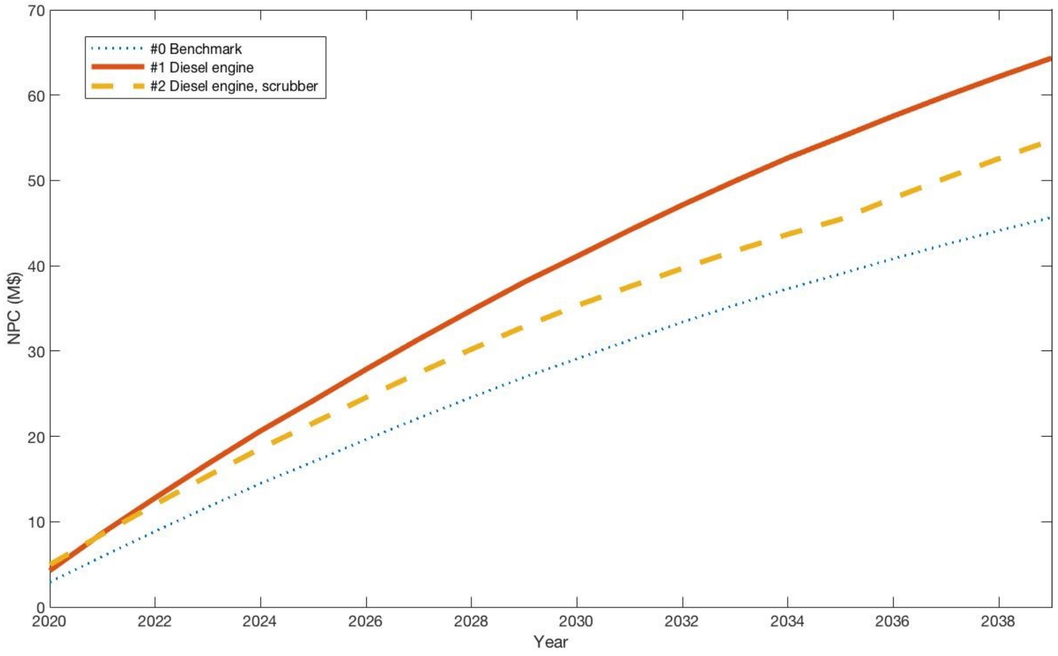


Figure 9.4: Total life-cycle costs

Table 9.7 gives the final results of the total life-cycle costs, taken into account a discount rate for the NPV analysis of 5%. Figure 9.5 gives a breakdown of those costs into the categories CAPEX, OPEX and voyage expenses. Without doing any investment and with switching to low sulphur fuels after 2020, the voyage expenses will rise with more than 40% as a consequence of the 2020 global sulphur limits. When investing in a scrubber, the voyage expenses will only increase with 7% compared to the benchmark. This increase of voyage expenses is mainly because the scrubber lifespan is 15 years, while we consider 20 years of operation. The remaining 5 years of operation, low sulphur fuel oil will be used to comply with the SO_x regulations. The total increase of life-cycle costs is almost 20% when considering a scrubber compared to the benchmark.

Table 9.7: Total life-cycle costs

#	***Total life-cycle costs***
0	45.7 M$
1	64.0 M$
2	54.6 M$

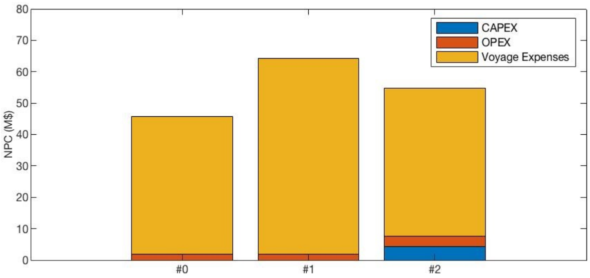


Figure 9.5: Subdivision of life-cycle costs

The capital expenses are given in Figure 9.6 and separated into costs related to abatement techniques and financing. The total investment of a scrubber amounts to 4.9 M$. As there is first one year of operation without a scrubber, the investment costs are discounted with 5% to 4.6 M$. Adding the financing in the NPV analysis gives an advantage of 0.3 M$. In the graph, the financing costs are negative, because the discount rate is higher than the interest rate.

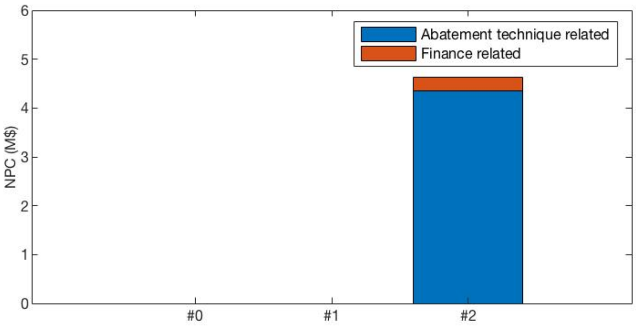


Figure 9.6: Subdivision of CAPEX

The operational expenses are given in Figure 9.7 and are separated into costs related to engines, fuels and abatement techniques. The OPEX of the engines are equal to each-other, as no different engines are considered. The OPEX related to fuels is very minor and no more than 10,000 $ in total over 20 remaining years. The OPEX related to the scrubber is 1.45 M$. The nominal costs are 0.15 M$ each year operating the scrubber.

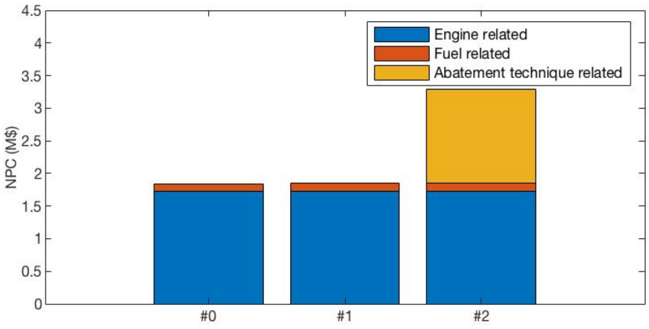


Figure 9.7: Case study 3, subdivision of OPEX

The voyage expenses are given in Figure 9.8 and are separated in costs related to fuels and loss of revenue. The latter is a result of a reduction in cargo capacity required by the installation of the equipment. As the scrubber has only a weight of 37.4 T, the reduction of cargo capacity can barely be seen in the graph and is negligible small. Other voyage expenses (port charges and carbon taxes) have been neglected. The reduction on port charges by being environmental friendly is very uncertain and often retroactively defined. Carbon taxes are not yet enforced, but might be in the future.

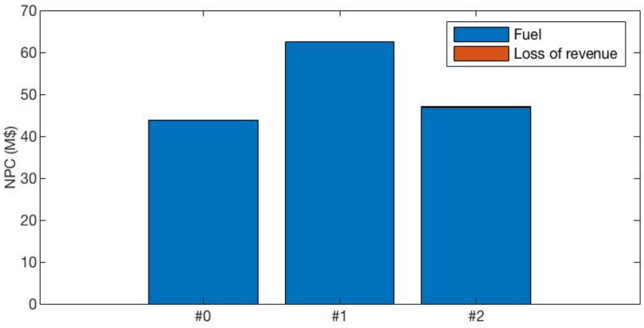


Figure 9.8: Subdivision of voyage expenses

9.4. Sensitivity analysis

To verify the influence of uncertain or variable parameters, a sensitivity analysis is conducted. A number of parameter variations have been applied to verify their influence on the total life-cycle costs of the different compliance options. The following parameter variations have been conducted:

- Variation of the scrubber price.
- Variation of the prices of the low sulphur fuels.
- A combination of a variation of the scrubber price and a variation of the prices of the low sulphur fuels.

Scrubber price

The influences of a variation of the scrubber price on the payback time of the scrubber are considered. The variation is done on the total scrubber price, including the equipment costs and installation costs. The payback times of the scrubber, corresponding to the parameter variations, are given in Table 9.8. Results show that the difference between the nominal payback time and the discounted payback time are limited and do not affect the results of the investment decision. It shows again, similar to the previous researches, that a variation of the scrubber price results in increased or decreased payback times of a few months.

Table 9.8: Influence of scrubber price on scrubber payback time

Price change	***Nominal payback time***	***Discounted payback time***
-40%	2.2 years	2.3 years
-20%	2.9 years	3.2 years
0%	3.7 years	4.1 years
+20%	4.4 years	5.1 years
+40%	5.2 years	6.1 years

Low sulphur fuel price

Figure 9.9 gives the results of the sensitivity analysis on the prices of low sulphur fuels. The HSFO price is kept unchanged. There can be concluded that a 20% drop of the low sulphur fuel price will make the scrubber business case unfavourable and brings up the payback time of a scrubber significantly. The price variation of low sulphur fuels also slightly affects compliance option 2 using a scrubber, as the scrubber has a limited lifespan of 15 years. This means that the ship will operate for the remaining 5 years on low sulphur fuels. In reality, the lifespan of a scrubber might not be so black and white. However, with respect to investment decisions, the effects of installing a scrubber for 15 years should be considered.

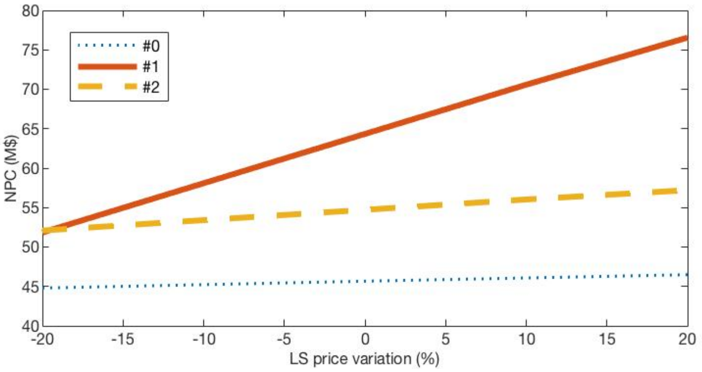


Figure 9.9: Sensitivity analysis on the low sulphur oil price

Table 9.9 gives the influences of the low sulphur oil price on the payback time of the scrubber, which shows a drastic increase of the payback time when the prices of low sulphur fuels drop. Again, similar to the previous cases, the low sulphur fuel prices can be considered as key parameters with respect to the scrubber payback time.

Table 9.9: Influence of the LS price on the scrubber payback time

LS change	*Nominal payback time*	*Discounted payback time*
-20%	11.9 years	>20.0 years
-10%	5.7 years	6.7 years
0%	3.7 years	4.1 years
+10%	2.7 years	3.0 years
+20%	2.2 years	2.4 years

Combination of the scrubber price and the low sulphur fuel price

The economic feasibility of scrubbers appeared to be largely influenced by the scrubber price and especially, by the price of low sulphur fuel oil. In this sensitivity analysis, the results of a combination of parameter variations will be shown. The first combination is given in Figure 9.10, where the low sulphur oil price and scrubber price are proportional varied. The graph looks similar to Figure 9.9, where only the low sulphur oil price is varied. However, the difference is that in this case the slope of the line corresponding to compliance option 2 is somewhat steeper, which means that both parameter variations amplify each-other to a certain extent.

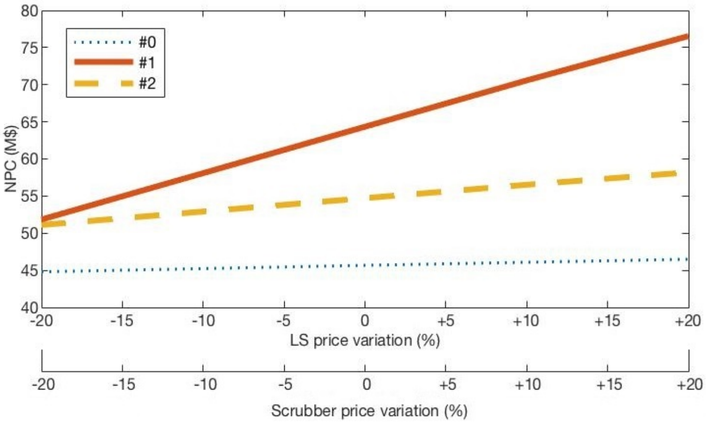


Figure 9.10: Proportional relationship between low sulphur oil price and scrubber price

Table 9.10 gives the influences of the proportional parameter variations on the scrubber payback times. The results show again that the low sulphur oil price is the dominating factor.

Table 9.10: Influence of the proportional relationship between low sulphur oil price and scrubber price on the scrubber payback time

LS price	*Scrubber price*	*Nominal payback time*	*Discounted payback time*
-20%	-20%	9.6 years	12.9 years
-10%	-10%	5.1 years	6.0 years
0%	0%	3.7 years	4.1 years
+10%	+10%	3.0 years	3.3 years
+20%	+20%	2.6 years	2.9 years

The second combination of parameter variations is given in Figure 9.11, where the low sulphur fuel oil price and scrubber price are inversely proportional varied. The slope of the line corresponding to compliance option 2 is more flat compared to Figure 9.9, where only the low sulphur oil price is varied. This means that both parameter variations compensate each other to a certain extent. However, the low sulphur oil price dominates.

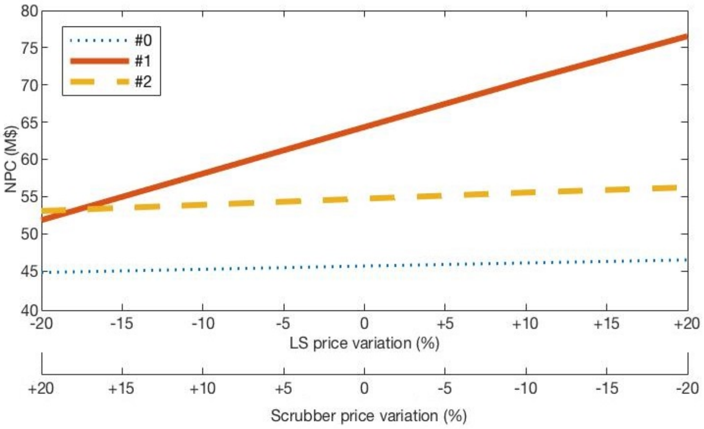


Figure 9.11: Inversely proportional relationship between low sulphur oil price and scrubber price

Table 9.11 gives the influences of the inverse proportional parameter variations on the scrubber payback times. Compared to the proportional parameter variations, the variation on the payback periods is more extreme. The benefits of both parameter variations are reflected on the payback time when increasing the low sulphur oil price and decreasing the scrubber price. On the other hand, the disadvantages of both parameter variations on the payback time when decreasing the low sulphur oil price and increasing the scrubber price are also reflected.

Table 9.11: Influence of the inverse proportional relationship between low sulphur oil price and scrubber price on the scrubber payback time

LS price	*Scrubber price*	*Nominal payback time*	*Discounted payback time*
-20%	+20%	14.3 years	>20 years
-10%	+10%	6.2 years	7.5 years
0%	0%	3.7 years	4.1 years
+10%	-10%	2.4 years	2.7 years
+20%	-20%	1.8 years	1.9 years

9.5. Conclusion

A specialized reefership is considered for retrofit in this case study. The vessel was delivered in 2010 and currently operating in the Caribanex line between West-Europe and the Caribbean. The ship operates with an average service speed of 17.4 knots, which is relative high. Port times are relatively long, as the loading and discharging of bananas and project cargo is time consuming. The compliance options that are considered are limited to the switch to low-sulphur fuels and the retrofit of a scrubber. The retrofit to a dual-fuel engine appeared to be not a feasible solution, due to the lack of an electronic injection control system on the existing engine. The replacement of the entire engine or retrofitting the engine with an electronic injection control system will be a too expensive exercise. Considering NO_x abatement techniques is not necessary, as the Baltic Klipper is built before 2011. Therefore, Tier II and Tier III regulations do not apply.

The retrofit of a scrubber is an attractive option, as this will reduce the nominal yearly running costs with more than 25%. The investment costs of 4.9 M$ pay themselves back in 3.7 years. Taking into account a discount rate of 5%, the discounted payback time is 4.1 years. The sensitivity analysis shows that the business case for a scrubber is highly sensitive to a variation of parameters. The dominating factor affecting the economic benefits of a scrubber is the low sulphur oil price, or the spread between high sulphur and low sulphur oils. A 20% increased low sulphur price may extend the nominal payback period to almost 12 years, while an increase of 20% will shorten the payback period to 2.2 years. A variation of the scrubber price including installation may weaken or strengthen the economic benefits of installing a scrubber. However, this will not be the dominating factor. The main focus should be on the price spread between high sulphur and low sulphur fuel oils.

10

Conclusions & recommendations

This thesis has described the research that has been performed to indicate the most cost effective life-cycle strategy regarding emission compliance after 2020 for the Seatrade fleet. A decision-support model is made to assess the financial feasibility of the compliance options for any particular ship. With the use of this tool, three case studies have been carried out to get a substantiated outcome for the different vessel types of the Seatrade fleet. This chapter gives the conclusions and recommendations that can be made up after assessing the case studies.

10.1. Conclusions

Shipowners are under large pressure at this moment to comply with rapidly evolving emission regulations. The sulphur regulations are the first upcoming and are expected to have major influences on the life-cycle costs of a ship. Besides the sulphur regulations, that regulate the SO_x emissions, regulations on NO_x emissions are already set and partly enforced. Currently available compliance methods are: (1) use low sulphur fuels, (2) install sulphur scrubbers or/and catalytic reduction systems, or (3) use LNG as a fuel. While all three alternatives are potential solutions for compliance, they each face operational, technological and economical challenges. The strategy of the IMO to reduce CO_2 emissions is still in progress and is expected to be introduced in April 2018.

The optimization models of existing research projects appeared to have it's limitations and especially, many simplifications. The decision support methodology that has found to be most appropriate to this case is a pure financial deterministic criterion, the NPV method. The key drivers for using this criterion are simplicity and the outcome of numbers that can be directly reflected to a real case, something which is not always the case for stochastic methods. Compared to other researches, the model that is used in this thesis is more complete and covers not only the basic parameters. Different financing methods, sludge disposal costs, insurance costs, loss of revenue, speed optimization and possible future carbon taxes are all covered in the model. The completeness of the optimization model makes this decision-support model unique and valuable for shipowners.

Newbuilding projects for Seatrade are currently focused on freezer vessels and specialized reefer containerships. Both vessel types have different operational profiles. The freezer vessels operate at relatively low speed and has exceptional high port times, while the containerships operate at relatively high speed and make the port calls as short as possible. Despite the significant difference of the operational profile, both results look similar. With respect to NO_x compliance, the installation of SCR systems appeared to be the most cost effective choice. The alternative of SCR systems is EGR, but this compliance option has too significant negative effects on the efficiency of the engine that it will be not the preferred option. Due to the long required endurance of both ships, dual-fuel engines using LNG will not be the most cost effective option. The large tank capacity that is required to meet the endurance requirements is driving up the capital costs to unaffordable limits. For the freezer vessels, LNG will never be beneficial. For the containerships, only if the specific gas tank costs halve, or if the tank capacity halves, the cost evaluation will be comparable to the alternative using low-sulphur fuels and installing a SCR system. A 20% reduction of the LNG price will lead to the same result, where the evaluation of dual-fuel engines is comparable with the alternative using low-sulphur fuels and installing a SCR system. However, even a combination of a positive variation of parameters will not results in significant cost advantages for LNG. For the installation of scrubbers, the story is different. Significant reductions on the voyage expenses lead to short payback periods. The discounted payback period for the freezer vessel is 4.5 years and 2.4 years for the containership. The sensitivity analysis shows that the price spread between HSFO and low sulphur fuels is the key parameter determining the benefits of a scrubber. A 20% drop of the low sulphur price multiplies the payback period with a factor 4 for the containership and for the freezer vessel, where the fuel consumption is significant lower, the payback time exceeds even the lifetime of the ship, meaning that the scrubber will never be payed back. The investment costs of a scrubber do have influence on the payback time. However, the effects are not so significant as they were for the low sulphur oil price. For the containerships, a rise of 40% of the equipment costs of a scrubber would lead to an increase of the payback time of 0.5 years, which is very minor.

The **existing ships** of the Seatrade fleet are almost all specialized reeferships. The average age of the fleet is 22 years. The main engines of all reeferships are fitted with a conventional camshaft, which makes the retrofit to dual-fuel operation a complex and difficult exercise that will be more expensive than installing a new engine on a newbuilding ship. As dual-fuel engine are already unaffordable for newbuilding projects, no further investigation is done for the retrofit of existing ships to dual-fuel. The retrofit of a scrubber is considered for the newest specialized reefership of the fleet, the Baltic Klipper. The results on the calculations for the retrofit of a scrubber shows a discounted payback time of 4.1 years. Similar to the newbuilding cases, the low sulphur oil price is the dominating parameter and has far more effects on the payback periods of the scrubber than other parameters, such as the price of a scrubber.

The results of the conducted case studies show in general that LNG will not be a viable option for the **Seatrade fleet**. The worldwide operational profiles of the ships require the gas tank sizes to be significant, which has negative effects on the investment costs and payback periods of the dual-fuel systems. Regarding Tier III NO_x compliance, which in fact only applies to newbuilding ships operating inside NECAs, the SCR systems appeared to be the most cost effective choice, as these systems have not, or barely, negative influences on the engine efficiency. Scrubbers might result in a significant reduction of fuel expenses. The discounted payback periods for all case studies is less than 5 years, which makes it an attractive business case. The real benefits of a scrubber depend on the market circumstances, among which the availability of high sulphur fuels after 2020 and the price development.

10.2. Recommendations

This research was conducted with the greatest care. However, like with any other research, there are many ways in which this research could have been performed differently or could have been extended. Based on the findings and conclusions of this research, several recommendations are to be considered regarding emission compliance for the shipping company Seatrade.

The results have shown that the installation of a scrubber appeared to be an attractive option. A recommendation is to further investigate the feasibility of a scrubber installation. Therefore, a ship specific case study needs to be performed focusing on the operational and technical implications that comes together with the installation of a scrubber. When specific calculations are made on the dimensions of the scrubber, the costs can also be defined more precisely rather than having a generic price. If there is decided to install a scrubber, the options for making long-term contracts with bunker suppliers need to be investigated. The volatility of bunker fuels is expected to increase when approaching 2020 due to the enforcement of the more strict global sulphur limits in fuel. Especially those operators who plan to run ships on scrubbers, unavailability is a realistic operational risk. Despite that, the opportunities that may arise if the HSFO will be available are also significant.

The main costs contributing to the dual-fuel business case are the costs for the gas storage system. A recommendation is to investigate the differences between the different tank types and investigate if any significant cost reduction is possible on this side.

The final message to the shipowners that arises from this research is "Be well prepared for the new sulphur limits and make a substantiated compliance choice in the run up to 2020". Many shipowners are in the wait-and-see approach and time is passing. This means that also the possibilities and time to prepare are reducing. If waiting longer and longer, yards are full booked and prices for retrofitting might rise.

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A

Finance sources in shipping

The money to finance ships comes from the pool of savings which are mainly held in the money markets, capital markets and the stock market. Nowadays, most of the investments are carried out by large funds. Accessing these financial markets can be done directly by the shipping company, or indirectly through an intermediary such as a commercial bank. Finance sources in shipping are divided into 4 categories. In Table A.1, all categories given and briefly explained.

Table A.1: Different types of ship finance [150]

Category	***Type of finance***	***Typical features***
Equity	Owner equity	Finance provided by owner from own funds and retained earnings.
	Limited partnership	Funds provided by partners.
	Ship fund	Shares in company bought privately by individuals or listed on stock exchange.
	Public offering	Shares sold by subscription on public stock exchange.
Mezzanine finance	Private placement	Debt with high interest rates and possibly equity rights.
Senior debt	Bond issue	Security issued in the capital market.
	Commercial bank loan	Loan provided by a bank.
	Seller's credit	Loan provided by the government to assist local shipyards.
	Private placement	Debt finance arranged privately.
Lease	Finance lease	Long term tax effective finance based on sale of a ship to a company which uses depriciation benefits.
	Operating lease	

Equity

Equity is the capital invested in a company free of debt, but the shareholders take a share in the profit and loss of the company [143]. Capital that comes from the owner is always equity, but there are other sources of equity as well. Limited partnership is one other source of equity. Limited partnerships are an aggregation of investors that will acquire a ship. The ship will then be chartered out. In many cases, the vessel is bought and leased back to the original ship owner or bought new and leased to the ship owner. The risk for the investors is limited to their initial investment [150]. Another source of equity is public offering, which is the least expensive way to increase the equity capital. In this case, shares are issued and sold to the public. The difference between public offering and a ship fund is if the shares are publicly tradable on the stock exchange, which is not the case for a ship fund [150].

Mezzanine finance

Mezzanine finance is a source of finance situated between equity and debt financing [150]. It has both properties associated with equity and with senior debt. In general, the mezzanine debt will take priority over equity in terms of repayment and security, but is subordinated to the senior debt. The mezzanine provider is entitled to a share of the capital gains of the company, comparable to shareholders, though at first does not share in the loss [150]. In many cases, the same syndicate of lenders will provide both the senior debt and the mezzanine debt, whilst the extent of the participation of each bank in the senior or the mezzanine debt will vary and depend on its risk appetite [80]. However, mezzanine finance has not been widely used as it is an very expensive financing method [143].

Senior debt

Debt financing is the most common type of ship financing [80]. The owner will borrow funds from a lender and will undertake to repay them within a certain time period. The provider obtains also certain rights, called mortgage. The most important right is that of being allowed to arrest the vessel and sell it in case of default of the owner [150]. Senior debt can be issued as bond, commercial bank loan, shipyard credit or private placement. The bond issue is very similar to public offering, as discussed in the category equity. Shares in the company are offered to the public to raise capital to buy the vessel. The major difference is that the influence of people holding the bond is very limited and instead of paying out divided, a bond pays out interest to the owner. Commercial bank loans and private placements are quite similar and have the same conditions. The only difference is that commercial bank loans are issued by banks and private placements by large funds, such as pension funds or insurance companies [150]. Shipyard credits are loans offered by governments in order to boost the local shipbuilding industry. This loan is usually used on top of bank financing [150].

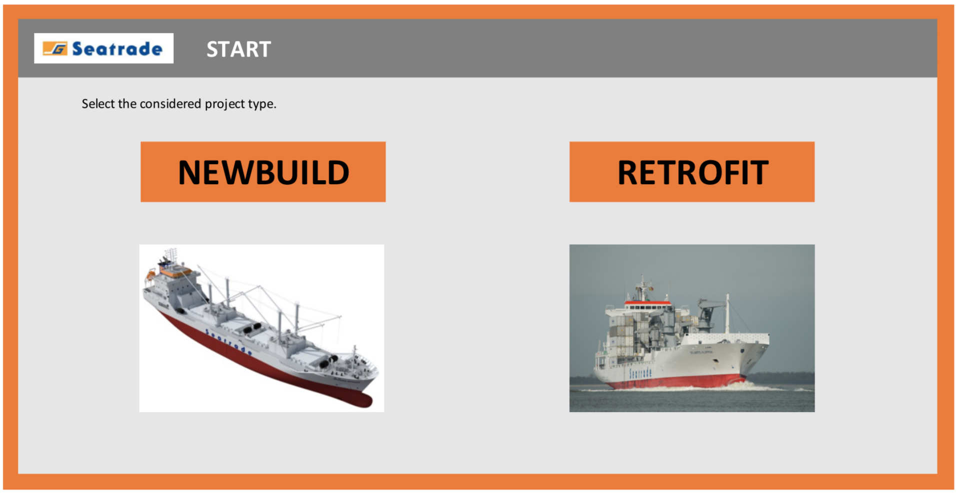
Lease

Leasing separates the use and ownership of the ship and is a stand-alone way of financing a ship. This means that the ship cannot be partially leased and partially covered by, for example, senior debt. Leasing is basically known as bareboat chartering. Financial lease and operating lease are two common types of leasing structures, which deal with the risks in different ways. Operating lease is used for hiring equipment and consumer durables, leaving the most of the risk with the lessor and at the end of the lease the equipment reverts to the lessor [143]. Financial leases are longer, covering a substantial part of the asset's life. The lessor has little involvement with the asset beyond owning it as all operating responsibilities fall on the lessee [143].

B

Tool manual

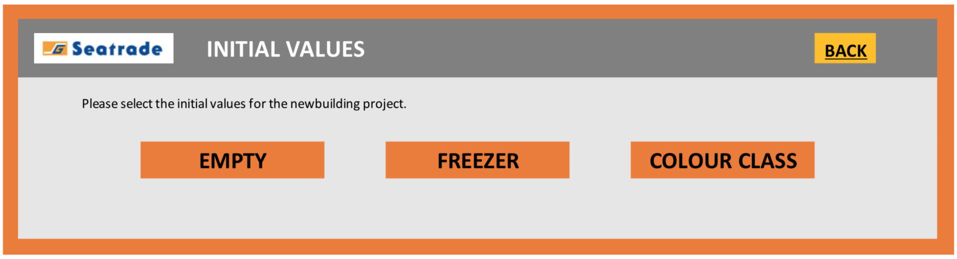
This appendix gives an outline of the steps to run through when analyzing a case in the tool. The data of the first case study will be used as an example. Figure B.1 is the start screen, where the choice can be made between a newbuilding project and a retrofit project. Both calculations are slightly different programmed. For the first case study, the "NEWBUILD" button is pressed.



Select the considered project type.

Figure B.1: Tool, start screen

The tool contains three pre-programmed input values, as shown in Figure B.2. When pressing one of the buttons, all input values are either left empty for a complete new case or represent the values as defined in the first or second case study. Afterwards, it is possible to change values if desired. For the first case study, there is opted for the initial values belonging to "FREEZER".



Please select the initial values for the newbuilding project.

Figure B.2: Tool, select initial values

The next screen is shown in Figure B.3. In the first column, all sub-screens with input values are given. The second column shows links to pages where the input can be checked and to verify whether the constraints are met. The third column gives to options to continue, with speed optimization or without speed optimization. Speed optimization means that in cases where the ship is both sailing inside SECAs and outside SECAs, the optimal speed is taken for both parts of the leg. Calculation of the optimum speeds takes some time, because it needs to be repeated for every compliance option and every single year. Therefore, there can be also opted to check the results without speed optimization. Speed optimization is rounded at 10th knots outside SECAs. This means that if the ship spent only a very limited fraction of the time inside SECAs, that the rounding inside SECAs can be much rougher.

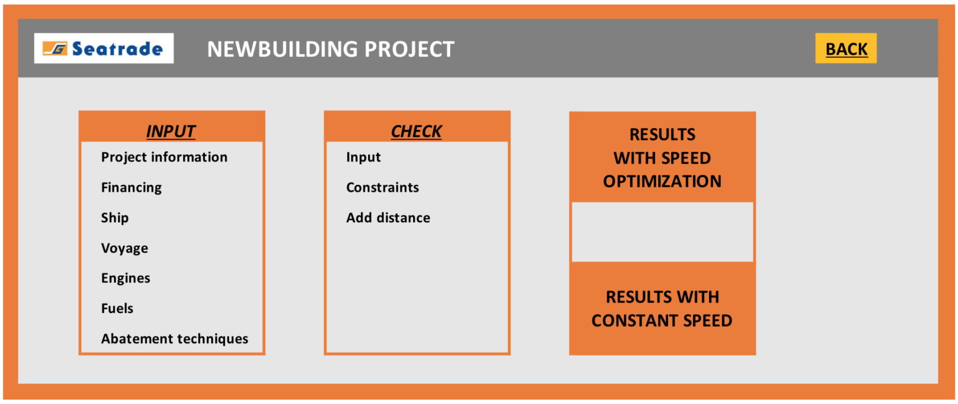
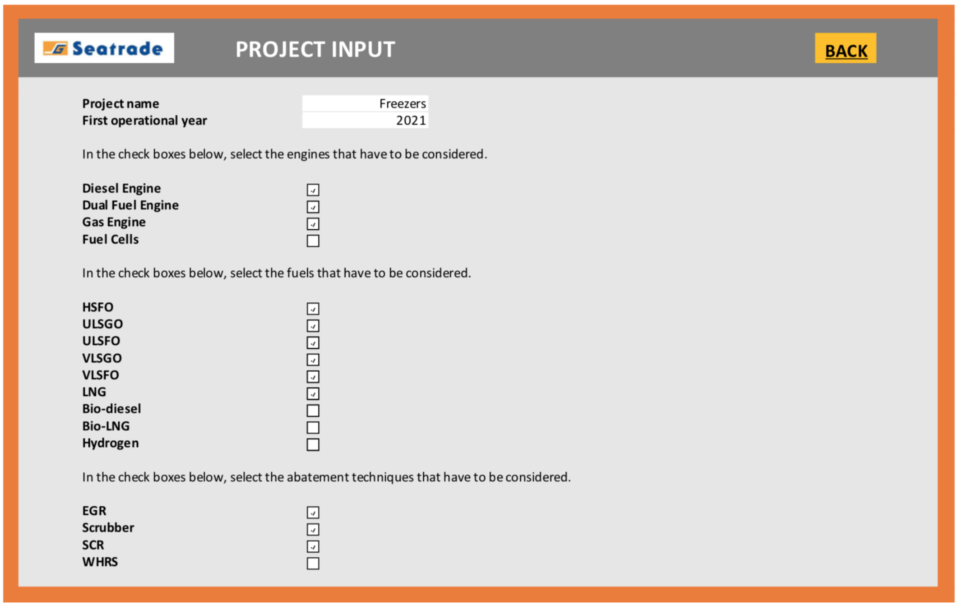


Figure B.3: Tool, input menu

In Figure B.4, the screen with general project input is given. The project name is used for reference. That afterwards, you are able to see which project data is loaded. The first operational year specifies at which year the calculations must start. For the Freezer, the first operational year is 2021. Theoretically, the ship will be delivered on 01-Jan-2021 12:00 a.m. One year prior to the first operational year, the initial investment costs are deducted. The moment of taking the initial investments into account is important for the NPV analysis.



Project name	Freezers
First operational year	2021

In the check boxes below, select the engines that have to be considered.

Diesel Engine	☑
Dual Fuel Engine	☑
Gas Engine	☑
Fuel Cells	☐

In the check boxes below, select the fuels that have to be considered.

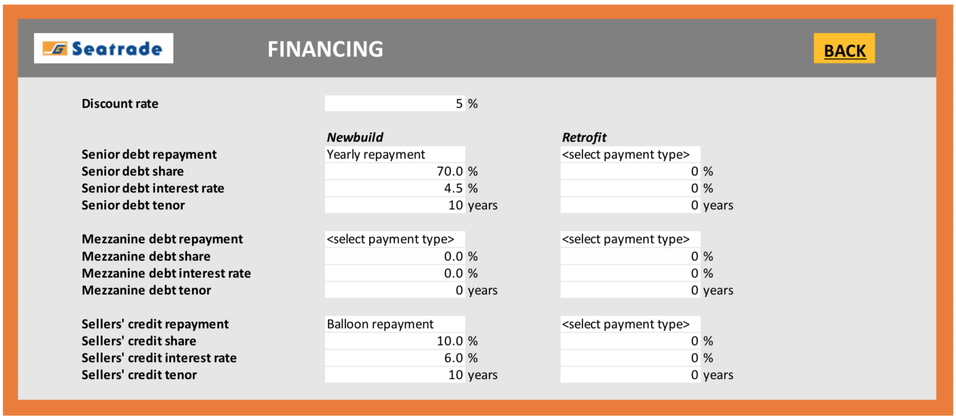
HSFO	☑
ULSGO	☑
ULSFO	☑
VLSGO	☑
VLSFO	☑
LNG	☑
Bio-diesel	☐
Bio-LNG	☐
Hydrogen	☐

In the check boxes below, select the abatement techniques that have to be considered.

EGR	☑
Scrubber	☑
SCR	☑
WHRS	☐

Figure B.4: Tool, project input

In Figure B.5, the parameters related to financing are specified. The discount rate is related to the NPV analysis. For both newbuilding and retrofitting projects, the finance methods can separately be defined. The newbuilding parameters are related to all engines and abatement techniques that are operational in the first year. Engines are always considered as a newbuilding project. Abatement techniques can also be installed after the first operational year. In that case, the abatement techniques are considered as retrofit.

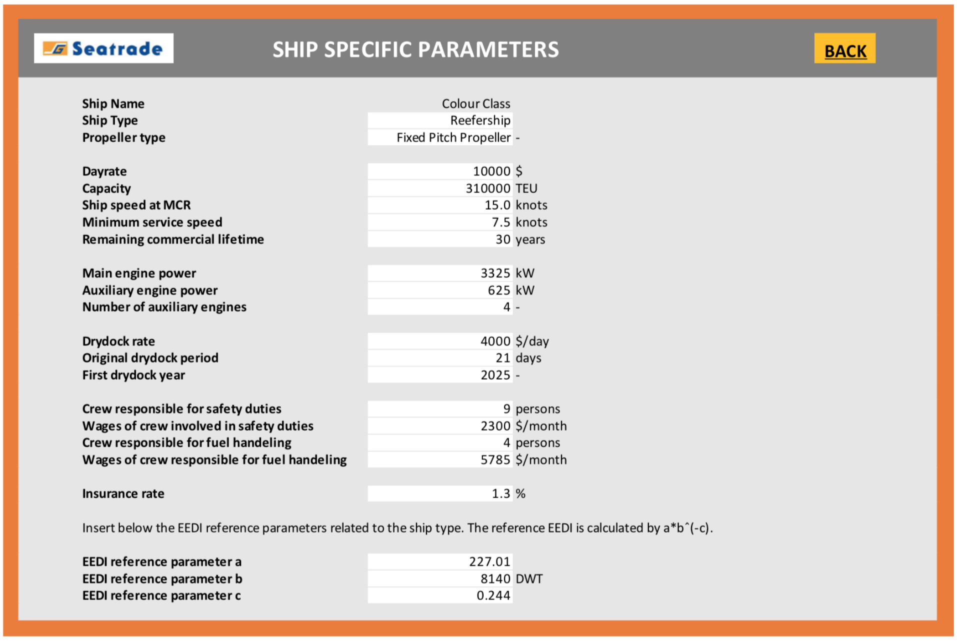


FINANCING

Discount rate	5	%		
	Newbuild		***Retrofit***	
Senior debt repayment	Yearly repayment		<select payment type>	
Senior debt share	70.0	%	0	%
Senior debt interest rate	4.5	%	0	%
Senior debt tenor	10	years	0	years
Mezzanine debt repayment	<select payment type>		<select payment type>	
Mezzanine debt share	0.0	%	0	%
Mezzanine debt interest rate	0.0	%	0	%
Mezzanine debt tenor	0	years	0	years
Sellers' credit repayment	Balloon repayment		<select payment type>	
Sellers' credit share	10.0	%	0	%
Sellers' credit interest rate	6.0	%	0	%
Sellers' credit tenor	10	years	0	years

Figure B.5: Tool, financing

In Figure B.5, the ship specific parameters are given. The ship type is required to use the correct way of calculating the loss of revenue. The propeller type is only used in defining the correct operational point of the engine. The minimum and maximum ship speed are used in the determination of the optimum speed for stretches covering both SECA and non-SECA distance. Both speeds define the boundaries of the speed optimization problem. The drydock rate is only used in cases where additional drydock time is required for the retrofit of abatement techniques. The drydock period and first drydock year are also used for the determination of the operational days in each year. A standard drydock interval of 5 years is used. The crew related data is used for the additional costs related to obtaining and retaining of the IGF training certificates. The number of crew responsible for each task should be the number of crew onboard. The calculation multiplies the input by 2 to account for the relief schedule. The attained EEDI is not included in the model. However, the input EEDI parameters are already included to be able to extent the model if necessary. The deadweight, EEDI reference parameter *b*, can be used to calculate the loss of revenue as a function of mass.



SHIP SPECIFIC PARAMETERS

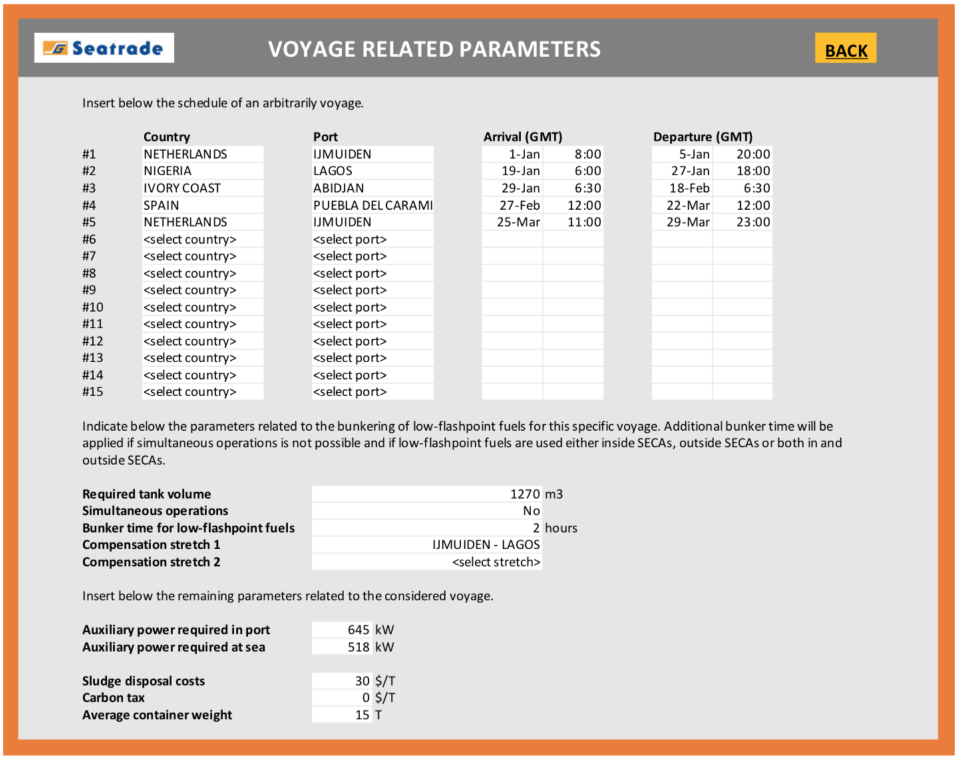
Ship Name	Colour Class	
Ship Type	Reefership	
Propeller type	Fixed Pitch Propeller	-
Dayrate	10000	$
Capacity	310000	TEU
Ship speed at MCR	15.0	knots
Minimum service speed	7.5	knots
Remaining commercial lifetime	30	years
Main engine power	3325	kW
Auxiliary engine power	625	kW
Number of auxiliary engines	4	-
Drydock rate	4000	$/day
Original drydock period	21	days
First drydock year	2025	-
Crew responsible for safety duties	9	persons
Wages of crew involved in safety duties	2300	$/month
Crew responsible for fuel handeling	4	persons
Wages of crew responsible for fuel handeling	5785	$/month
Insurance rate	1.3	%

Insert below the EEDI reference parameters related to the ship type. The reference EEDI is calculated by a*bˆ(-c).

EEDI reference parameter a	227.01	
EEDI reference parameter b	8140	DWT
EEDI reference parameter c	0.244	

Figure B.6: Tool, ship specific parameters

In Figure B.7, the voyage related parameters are given. The port schedule of a voyage is used as input for the operational profile. By the use of a drop-down menu, ports can be selected. The selection of the country is not required but makes it easy to select the ports, as the port drop-down menu will only give the ports in the selected country. The sheet is linked to a database containing the total distances between ports and the distance inside SECAs. However, this database is not complete. In the check page that is given in Figure B.20, there can be checked whether or not the distances for the considered voyage are entered into the database. The second block of information is only applicable to the use of LNG and hydrogen. The required auxiliary loads that need to be specified are applicable to the entire voyage. As the auxiliary power is definitely not constant, a weighted average needs to be taken.



VOYAGE RELATED PARAMETERS

Insert below the schedule of an arbitrarily voyage.

	Country	Port	Arrival (GMT)		Departure (GMT)	
#1	NETHERLANDS	IJMUIDEN	1-Jan	8:00	5-Jan	20:00
#2	NIGERIA	LAGOS	19-Jan	6:00	27-Jan	18:00
#3	IVORY COAST	ABIDJAN	29-Jan	6:30	18-Feb	6:30
#4	SPAIN	PUEBLA DEL CARAMI	27-Feb	12:00	22-Mar	12:00
#5	NETHERLANDS	IJMUIDEN	25-Mar	11:00	29-Mar	23:00
#6	<select country>	<select port>				
#7	<select country>	<select port>				
#8	<select country>	<select port>				
#9	<select country>	<select port>				
#10	<select country>	<select port>				
#11	<select country>	<select port>				
#12	<select country>	<select port>				
#13	<select country>	<select port>				
#14	<select country>	<select port>				
#15	<select country>	<select port>				

Indicate below the parameters related to the bunkering of low-flashpoint fuels for this specific voyage. Additional bunker time will be applied if simultaneous operations is not possible and if low-flashpoint fuels are used either inside SECAs, outside SECAs or both in and outside SECAs.

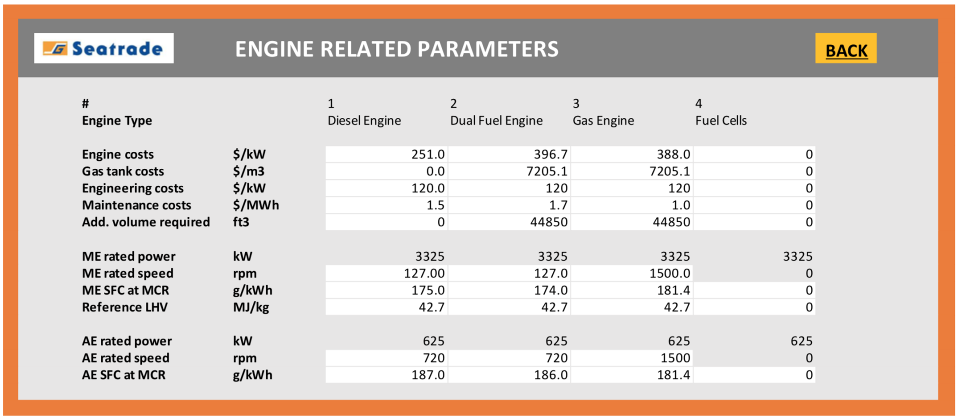
Required tank volume	1270	m3
Simultaneous operations	No	
Bunker time for low-flashpoint fuels	2	hours
Compensation stretch 1	IJMUIDEN - LAGOS	
Compensation stretch 2	<select stretch>	

Insert below the remaining parameters related to the considered voyage.

Auxiliary power required in port	645	kW
Auxiliary power required at sea	518	kW
Sludge disposal costs	30	$/T
Carbon tax	0	$/T
Average container weight	15	T

Figure B.7: Tool, voyage related parameters

In Figure B.8, the engine related parameters are given. These parameters are in principle independent from the case study and a result of the cost & data analysis. Only the additional volume required varies per case study. This parameter is related to the loss of revenue and specifies the cargo capacity that is reduced as a result of the placement of gas tanks.

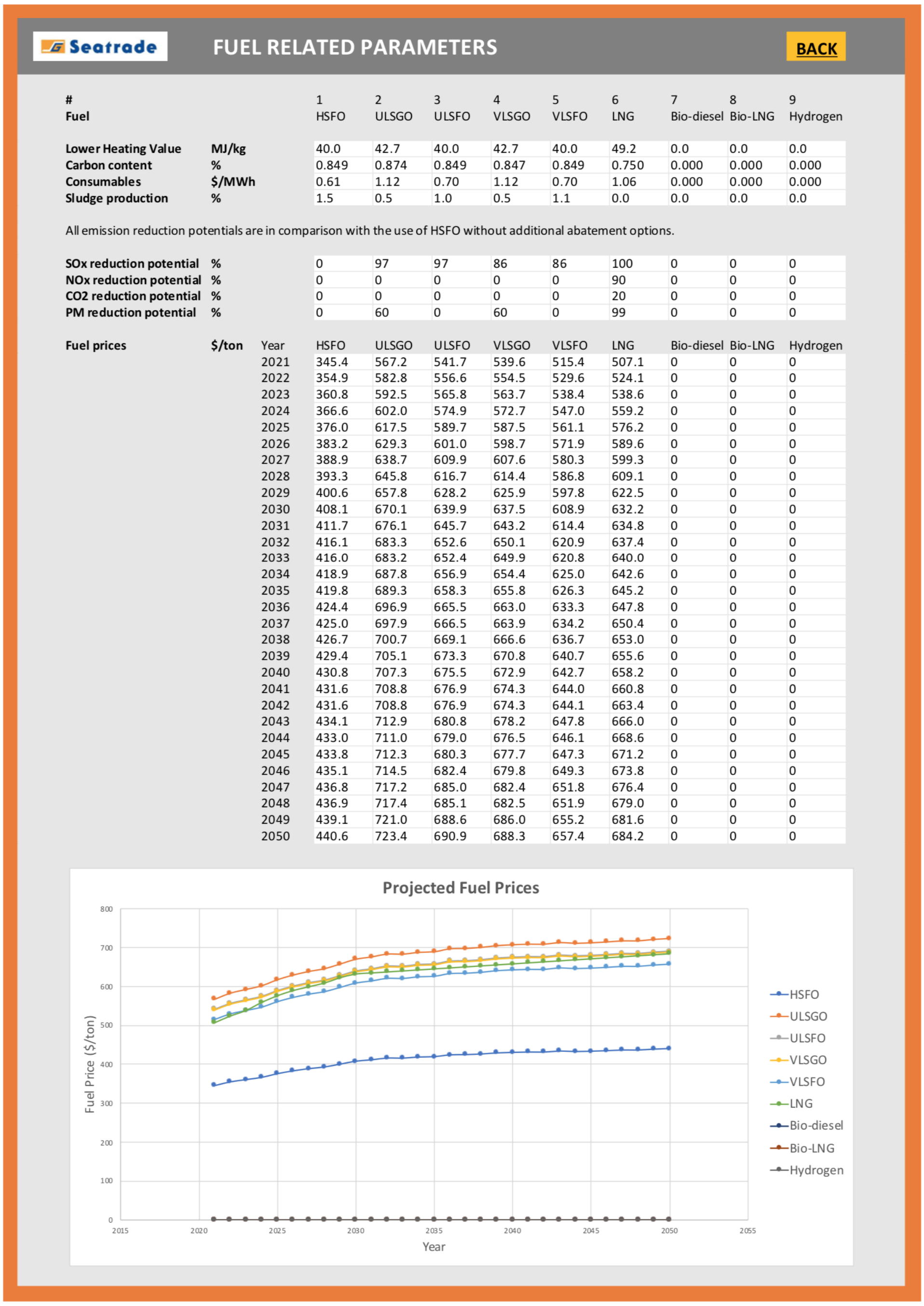


ENGINE RELATED PARAMETERS

#		1	2	3	4
Engine Type		Diesel Engine	Dual Fuel Engine	Gas Engine	Fuel Cells
Engine costs	**$/kW**	251.0	396.7	388.0	0
Gas tank costs	**$/m3**	0.0	7205.1	7205.1	0
Engineering costs	**$/kW**	120.0	120	120	0
Maintenance costs	**$/MWh**	1.5	1.7	1.0	0
Add. volume required	**ft3**	0	44850	44850	0
ME rated power	**kW**	3325	3325	3325	3325
ME rated speed	**rpm**	127.00	127.0	1500.0	0
ME SFC at MCR	**g/kWh**	175.0	174.0	181.4	0
Reference LHV	**MJ/kg**	42.7	42.7	42.7	0
AE rated power	**kW**	625	625	625	625
AE rated speed	**rpm**	720	720	1500	0
AE SFC at MCR	**g/kWh**	187.0	186.0	181.4	0

Figure B.8: Tool, engine related parameters

In Figure B.9, the fuel related parameters are given. The parameters, except the fuel prices, are in principle constant for every case. The SO_x and NO_x reduction potentials are used to check compliance with IMO regulations. The CO_2 and PM reduction potentials are not used in the calculations. The carbon tax related to different fuels is related to the carbon content, which can indirect be seen as a CO_2 reduction. The fuel prices can be either inserted manually or by using a formula.



FUEL RELATED PARAMETERS

#		1	2	3	4	5	6	7	8	9
Fuel		HSFO	ULSGO	ULSFO	VLSGO	VLSFO	LNG	Bio-diesel	Bio-LNG	Hydrogen
Lower Heating Value	MJ/kg	40.0	42.7	40.0	42.7	40.0	49.2	0.0	0.0	0.0
Carbon content	%	0.849	0.874	0.849	0.847	0.849	0.750	0.000	0.000	0.000
Consumables	$/MWh	0.61	1.12	0.70	1.12	0.70	1.06	0.000	0.000	0.000
Sludge production	%	1.5	0.5	1.0	0.5	1.1	0.0	0.0	0.0	0.0

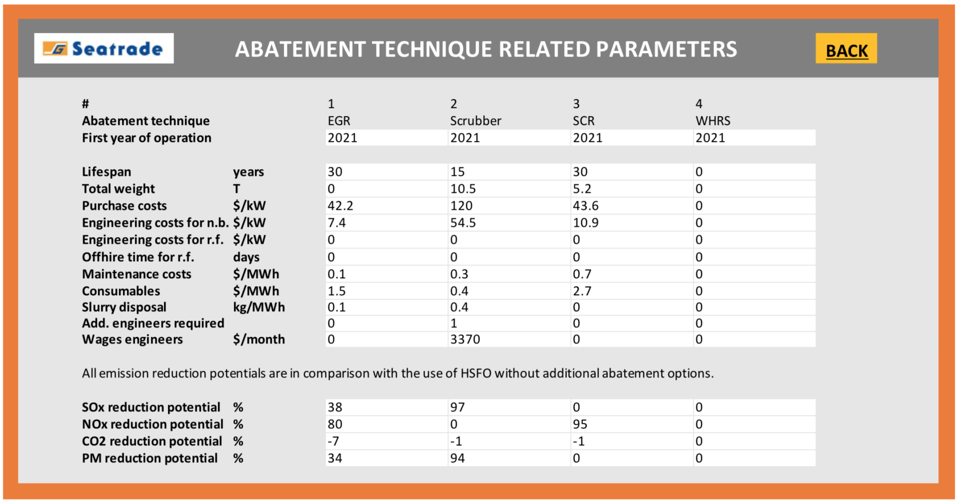
All emission reduction potentials are in comparison with the use of HSFO without additional abatement options.

SOx reduction potential	%	0	97	97	86	86	100	0	0	0
NOx reduction potential	%	0	0	0	0	0	90	0	0	0
CO2 reduction potential	%	0	0	0	0	0	20	0	0	0
PM reduction potential	%	0	60	0	60	0	99	0	0	0

Fuel prices	$/ton	Year	HSFO	ULSGO	ULSFO	VLSGO	VLSFO	LNG	Bio-diesel	Bio-LNG	Hydrogen
		2021	345.4	567.2	541.7	539.6	515.4	507.1	0	0	0
		2022	354.9	582.8	556.6	554.5	529.6	524.1	0	0	0
		2023	360.8	592.5	565.8	563.7	538.4	538.6	0	0	0
		2024	366.6	602.0	574.9	572.7	547.0	559.2	0	0	0
		2025	376.0	617.5	589.7	587.5	561.1	576.2	0	0	0
		2026	383.2	629.3	601.0	598.7	571.9	589.6	0	0	0
		2027	388.9	638.7	609.9	607.6	580.3	599.3	0	0	0
		2028	393.3	645.8	616.7	614.4	586.8	609.1	0	0	0
		2029	400.6	657.8	628.2	625.9	597.8	622.5	0	0	0
		2030	408.1	670.1	639.9	637.5	608.9	632.2	0	0	0
		2031	411.7	676.1	645.7	643.2	614.4	634.8	0	0	0
		2032	416.1	683.3	652.6	650.1	620.9	637.4	0	0	0
		2033	416.0	683.2	652.4	649.9	620.8	640.0	0	0	0
		2034	418.9	687.8	656.9	654.4	625.0	642.6	0	0	0
		2035	419.8	689.3	658.3	655.8	626.3	645.2	0	0	0
		2036	424.4	696.9	665.5	663.0	633.3	647.8	0	0	0
		2037	425.0	697.9	666.5	663.9	634.2	650.4	0	0	0
		2038	426.7	700.7	669.1	666.6	636.7	653.0	0	0	0
		2039	429.4	705.1	673.3	670.8	640.7	655.6	0	0	0
		2040	430.8	707.3	675.5	672.9	642.7	658.2	0	0	0
		2041	431.6	708.8	676.9	674.3	644.0	660.8	0	0	0
		2042	431.6	708.8	676.9	674.3	644.1	663.4	0	0	0
		2043	434.1	712.9	680.8	678.2	647.8	666.0	0	0	0
		2044	433.0	711.0	679.0	676.5	646.1	668.6	0	0	0
		2045	433.8	712.3	680.3	677.7	647.3	671.2	0	0	0
		2046	435.1	714.5	682.4	679.8	649.3	673.8	0	0	0
		2047	436.8	717.2	685.0	682.4	651.8	676.4	0	0	0
		2048	436.9	717.4	685.1	682.5	651.9	679.0	0	0	0
		2049	439.1	721.0	688.6	686.0	655.2	681.6	0	0	0
		2050	440.6	723.4	690.9	688.3	657.4	684.2	0	0	0

Figure B.9: Tool, fuel related parameters

In Figure B.10, the abatement technique related parameters are given. If the first operational year is set equal to the first operational year of the ship, the installation is done during newbuilding and for the calculations, no additional drydock days are accounted. If the first operational year of abatement techniques is after the first operational year of the ship, additional drydock days might be accounted and the finance sources as specified in Figure B.5 for retrofit are used. The possibility to add additional engineers for the operation and maintenance is added. In this case, one additional engineer is accounted for the operation and maintenance of a scrubber.



ABATEMENT TECHNIQUE RELATED PARAMETERS

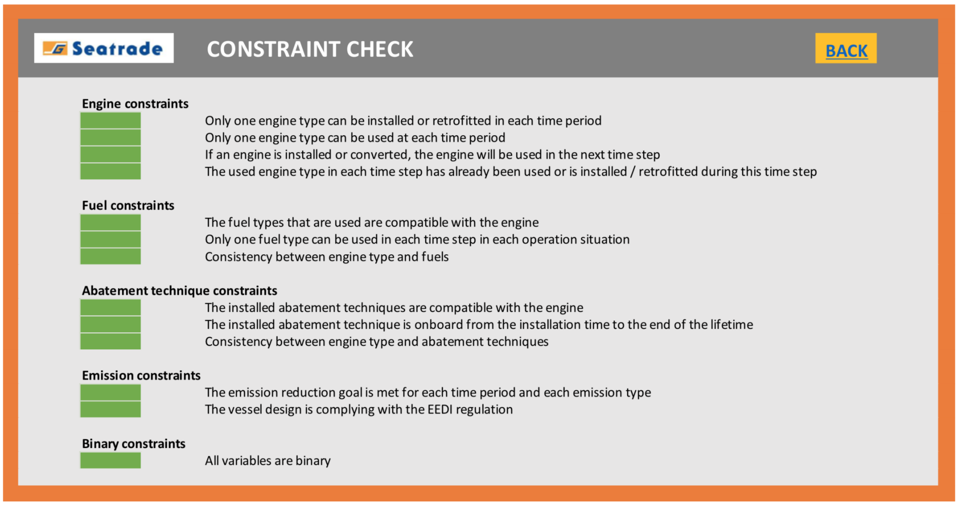
#		1	2	3	4
Abatement technique		EGR	Scrubber	SCR	WHRS
First year of operation		2021	2021	2021	2021
Lifespan	**years**	30	15	30	0
Total weight	**T**	0	10.5	5.2	0
Purchase costs	**$/kW**	42.2	120	43.6	0
Engineering costs for n.b.	**$/kW**	7.4	54.5	10.9	0
Engineering costs for r.f.	**$/kW**	0	0	0	0
Offhire time for r.f.	**days**	0	0	0	0
Maintenance costs	**$/MWh**	0.1	0.3	0.7	0
Consumables	**$/MWh**	1.5	0.4	2.7	0
Slurry disposal	**kg/MWh**	0.1	0.4	0	0
Add. engineers required		0	1	0	0
Wages engineers	**$/month**	0	3370	0	0

All emission reduction potentials are in comparison with the use of HSFO without additional abatement options.

SOx reduction potential	**%**	38	97	0	0
NOx reduction potential	**%**	80	0	95	0
CO2 reduction potential	**%**	-7	-1	-1	0
PM reduction potential	**%**	34	94	0	0

Figure B.10: Tool, abatement technique related parameters

The constraints check can be addressed via the input menu as shown in Figure B.3. The constraints check itselves is given in Figure B.19 and shows whether or not all the constraints are met. The constraints are matching with the constraints described in Chapter 5.3.



CONSTRAINT CHECK

Engine constraints

🟩 Only one engine type can be installed or retrofitted in each time period
🟩 Only one engine type can be used at each time period
🟩 If an engine is installed or converted, the engine will be used in the next time step
🟩 The used engine type in each time step has already been used or is installed / retrofitted during this time step

Fuel constraints

🟩 The fuel types that are used are compatible with the engine
🟩 Only one fuel type can be used in each time step in each operation situation
🟩 Consistency between engine type and fuels

Abatement technique constraints

🟩 The installed abatement techniques are compatible with the engine
🟩 The installed abatement technique is onboard from the installation time to the end of the lifetime
🟩 Consistency between engine type and abatement techniques

Emission constraints

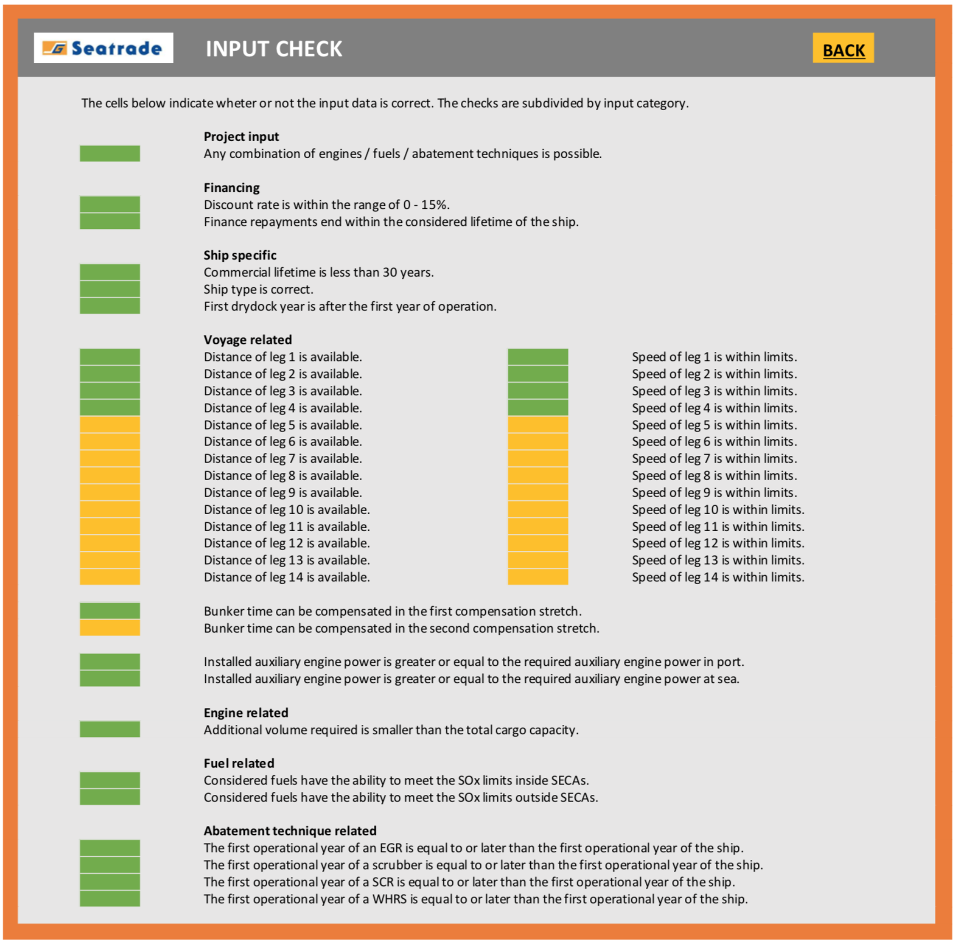
🟩 The emission reduction goal is met for each time period and each emission type
🟩 The vessel design is complying with the EEDI regulation

Binary constraints

🟩 All variables are binary

Figure B.11: Tool, constraints check

In Figure B.20, the input parameters are checked. The cells indicate green if the input is in the correct format and the correct range. The cells indicate yellow if the parameters are not considered. The cells indicate red if parameters are in the wrong format or out of range.



The cells below indicate wheter or not the input data is correct. The checks are subdivided by input category.

Project input
🟩 Any combination of engines / fuels / abatement techniques is possible.

Financing
🟩 Discount rate is within the range of 0 - 15%.
🟩 Finance repayments end within the considered lifetime of the ship.

Ship specific
🟩 Commercial lifetime is less than 30 years.
🟩 Ship type is correct.
🟩 First drydock year is after the first year of operation.

Voyage related

🟩	Distance of leg 1 is available.	🟩	Speed of leg 1 is within limits.
🟩	Distance of leg 2 is available.	🟩	Speed of leg 2 is within limits.
🟩	Distance of leg 3 is available.	🟩	Speed of leg 3 is within limits.
🟩	Distance of leg 4 is available.	🟩	Speed of leg 4 is within limits.
🟨	Distance of leg 5 is available.	🟨	Speed of leg 5 is within limits.
🟨	Distance of leg 6 is available.	🟨	Speed of leg 6 is within limits.
🟨	Distance of leg 7 is available.	🟨	Speed of leg 7 is within limits.
🟨	Distance of leg 8 is available.	🟨	Speed of leg 8 is within limits.
🟨	Distance of leg 9 is available.	🟨	Speed of leg 9 is within limits.
🟨	Distance of leg 10 is available.	🟨	Speed of leg 10 is within limits.
🟨	Distance of leg 11 is available.	🟨	Speed of leg 11 is within limits.
🟨	Distance of leg 12 is available.	🟨	Speed of leg 12 is within limits.
🟨	Distance of leg 13 is available.	🟨	Speed of leg 13 is within limits.
🟨	Distance of leg 14 is available.	🟨	Speed of leg 14 is within limits.

🟩 Bunker time can be compensated in the first compensation stretch.
🟨 Bunker time can be compensated in the second compensation stretch.

🟩 Installed auxiliary engine power is greater or equal to the required auxiliary engine power in port.
🟩 Installed auxiliary engine power is greater or equal to the required auxiliary engine power at sea.

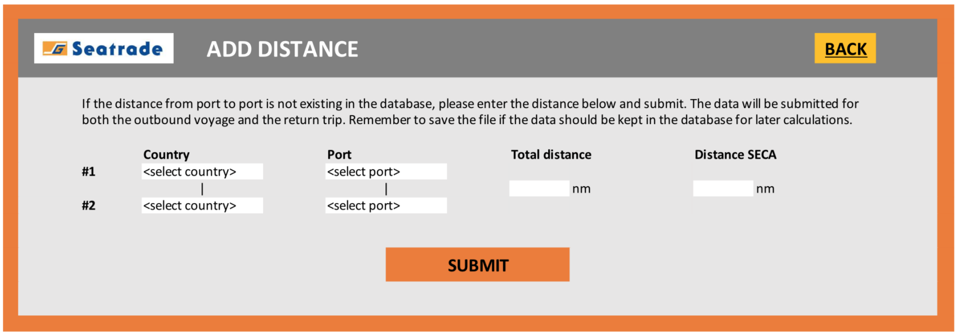
Engine related
🟩 Additional volume required is smaller than the total cargo capacity.

Fuel related
🟩 Considered fuels have the ability to meet the SOx limits inside SECAs.
🟩 Considered fuels have the ability to meet the SOx limits outside SECAs.

Abatement technique related
🟩 The first operational year of an EGR is equal to or later than the first operational year of the ship.
🟩 The first operational year of a scrubber is equal to or later than the first operational year of the ship.
🟩 The first operational year of a SCR is equal to or later than the first operational year of the ship.
🟩 The first operational year of a WHRS is equal to or later than the first operational year of the ship.

Figure B.12: Tool, input check

To calculate the operational profile, the voyage related input data is coupled to a database which contains the distance between all ports in the world. Unfortunately, the database is not filled and contains only those port-to-port distances that are calculated before. In the 'Input check' screen, there can be checked whether or not all required distances are available in the database. If that is not the case, the port-to-port distances can be entered manually in the interface that is shown in Figure B.13.



If the distance from port to port is not existing in the database, please enter the distance below and submit. The data will be submitted for both the outbound voyage and the return trip. Remember to save the file if the data should be kept in the database for later calculations.

	Country	Port	Total distance	Distance SECA
#1	<select country>	<select port>	nm	nm
#2	<select country>	<select port>		

Figure B.13: Tool, add distance

In Figure B.14, the results menu is given. This screen appears after running the results with or without speed optimization. From here, you can go back to the input menu or see a detailed description of the results.

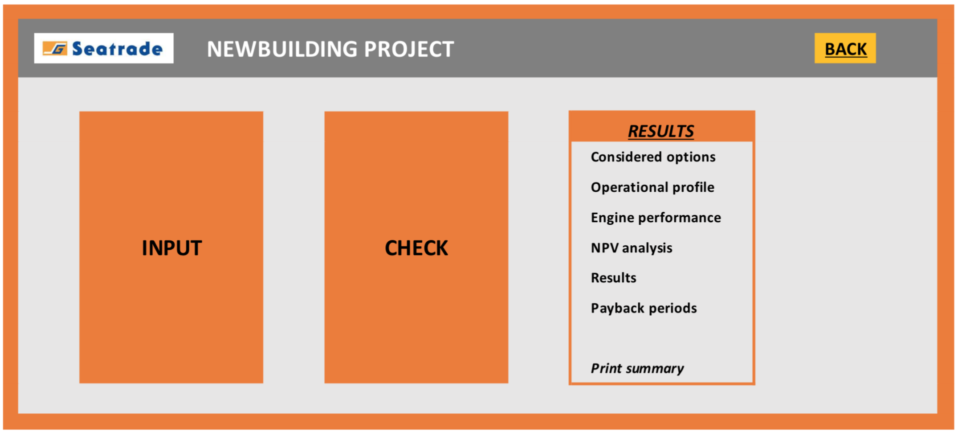
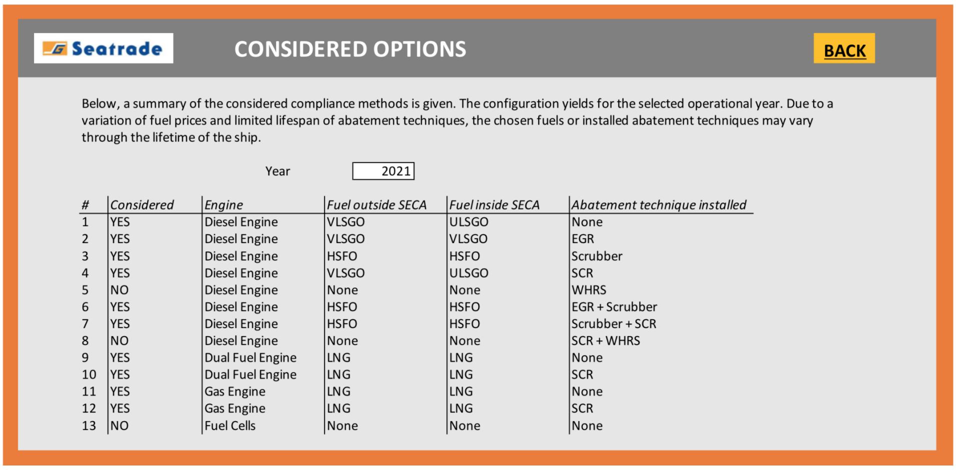


Figure B.14: Tool, results menu

In Figure B.15, the considered options are given. The default results are given for the first operational year. By use of a drop-down menu, the options can be considered for other years. The results can be different if abatement techniques are retrofitted, abatement techniques have a limited lifespan, fuel prices changes or if regulation changes. Note that the numbers of the compliance options do not match with the numbers that are used in the case studies of this report.



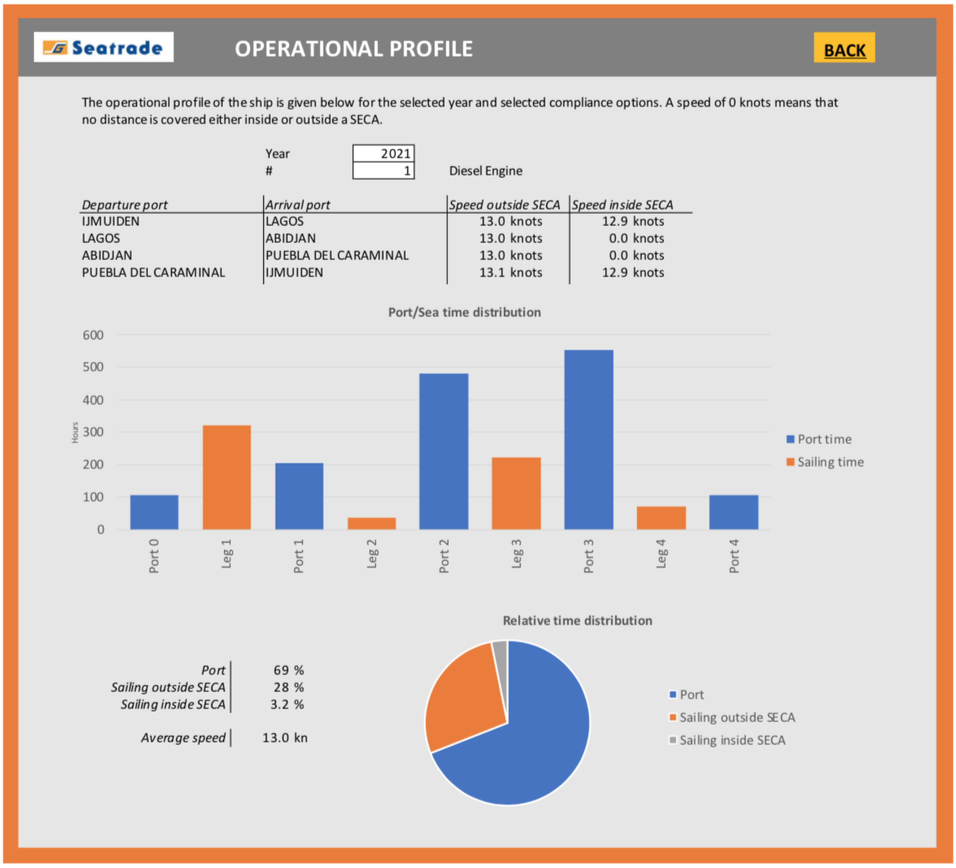
Below, a summary of the considered compliance methods is given. The configuration yields for the selected operational year. Due to a variation of fuel prices and limited lifespan of abatement techniques, the chosen fuels or installed abatement techniques may vary through the lifetime of the ship.

Year 2021

#	*Considered*	*Engine*	*Fuel outside SECA*	*Fuel inside SECA*	*Abatement technique installed*
1	YES	Diesel Engine	VLSGO	ULSGO	None
2	YES	Diesel Engine	VLSGO	VLSGO	EGR
3	YES	Diesel Engine	HSFO	HSFO	Scrubber
4	YES	Diesel Engine	VLSGO	ULSGO	SCR
5	NO	Diesel Engine	None	None	WHRS
6	YES	Diesel Engine	HSFO	HSFO	EGR + Scrubber
7	YES	Diesel Engine	HSFO	HSFO	Scrubber + SCR
8	NO	Diesel Engine	None	None	SCR + WHRS
9	YES	Dual Fuel Engine	LNG	LNG	None
10	YES	Dual Fuel Engine	LNG	LNG	SCR
11	YES	Gas Engine	LNG	LNG	None
12	YES	Gas Engine	LNG	LNG	SCR
13	NO	Fuel Cells	None	None	None

Figure B.15: Tool, considered options

In Figure B.16, the operation profile of the case study is given. The default results are given for the first operational year and the first compliance option. By use of a drop-down menu, other years and options can be selected.



The operational profile of the ship is given below for the selected year and selected compliance options. A speed of 0 knots means that no distance is covered either inside or outside a SECA.

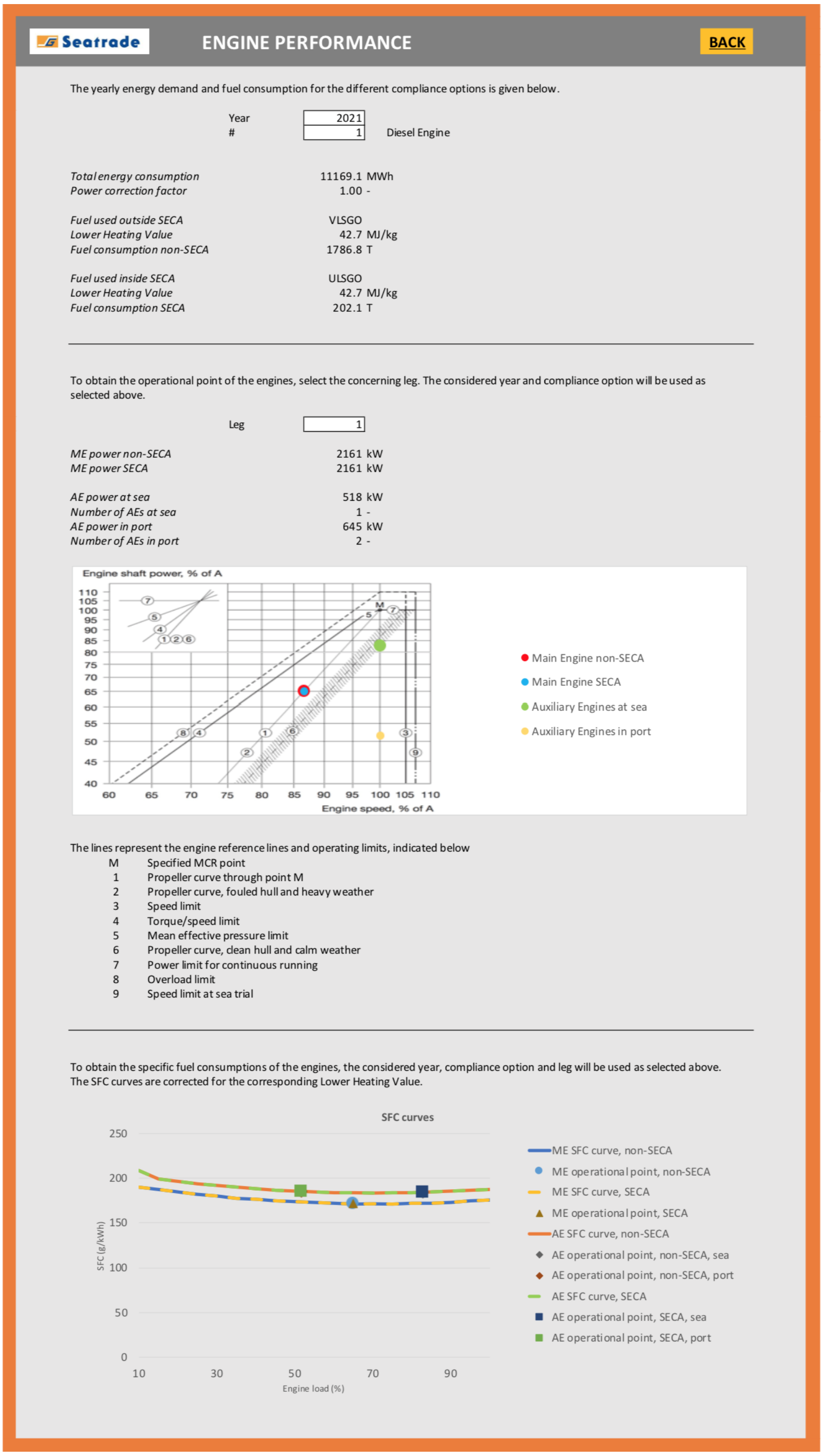
Year 2021
\# 1 Diesel Engine

Departure port	*Arrival port*	*Speed outside SECA*	*Speed inside SECA*
IJMUIDEN	LAGOS	13.0 knots	12.9 knots
LAGOS	ABIDJAN	13.0 knots	0.0 knots
ABIDJAN	PUEBLA DEL CARAMINAL	13.0 knots	0.0 knots
PUEBLA DEL CARAMINAL	IJMUIDEN	13.1 knots	12.9 knots

Port	69 %
Sailing outside SECA	28 %
Sailing inside SECA	3.2 %
Average speed	13.0 kn

Figure B.16: Tool, operational profile

In Figure B.17, the fuel consumptions, engine powers and specific fuel consumptions are given. The default results are given for the first operational year, the first compliance option and the first leg. With a drop-down menu, other years, options and legs can be selected.



ENGINE PERFORMANCE

The yearly energy demand and fuel consumption for the different compliance options is given below.

Year	2021	
#	1	Diesel Engine

Total energy consumption	11169.1	MWh
Power correction factor	1.00	-
Fuel used outside SECA	VLSGO	
Lower Heating Value	42.7	MJ/kg
Fuel consumption non-SECA	1786.8	T
Fuel used inside SECA	ULSGO	
Lower Heating Value	42.7	MJ/kg
Fuel consumption SECA	202.1	T

To obtain the operational point of the engines, select the concerning leg. The considered year and compliance option will be used as selected above.

Leg 1

ME power non-SECA	2161	kW
ME power SECA	2161	kW
AE power at sea	518	kW
Number of AEs at sea	1	-
AE power in port	645	kW
Number of AEs in port	2	-

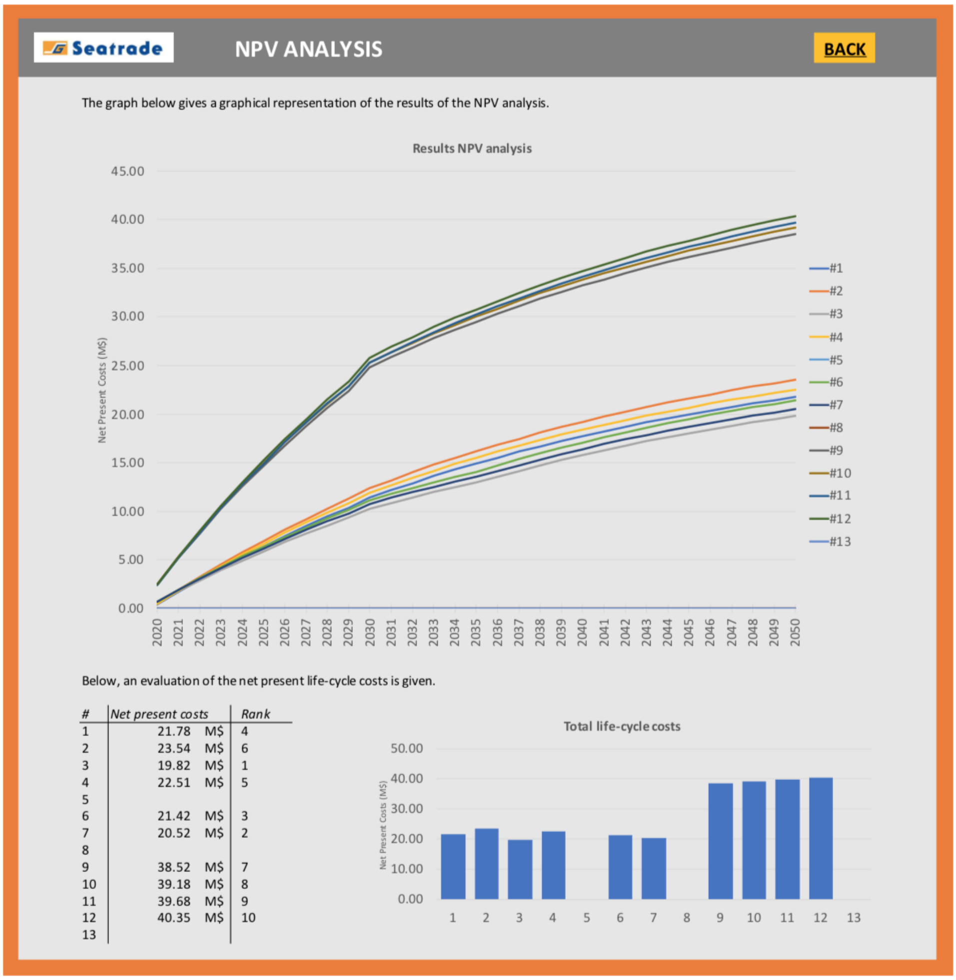
The lines represent the engine reference lines and operating limits, indicated below

M	Specified MCR point
1	Propeller curve through point M
2	Propeller curve, fouled hull and heavy weather
3	Speed limit
4	Torque/speed limit
5	Mean effective pressure limit
6	Propeller curve, clean hull and calm weather
7	Power limit for continuous running
8	Overload limit
9	Speed limit at sea trial

To obtain the specific fuel consumptions of the engines, the considered year, compliance option and leg will be used as selected above.
The SFC curves are corrected for the corresponding Lower Heating Value.

Figure B.17: Tool, engine performance

In Figure B.18, the results of the NPV analysis are given for the entire lifetime of the ship. Below the graph, the total life-cycle costs of the different compliance options are given and ranked.



NPV ANALYSIS

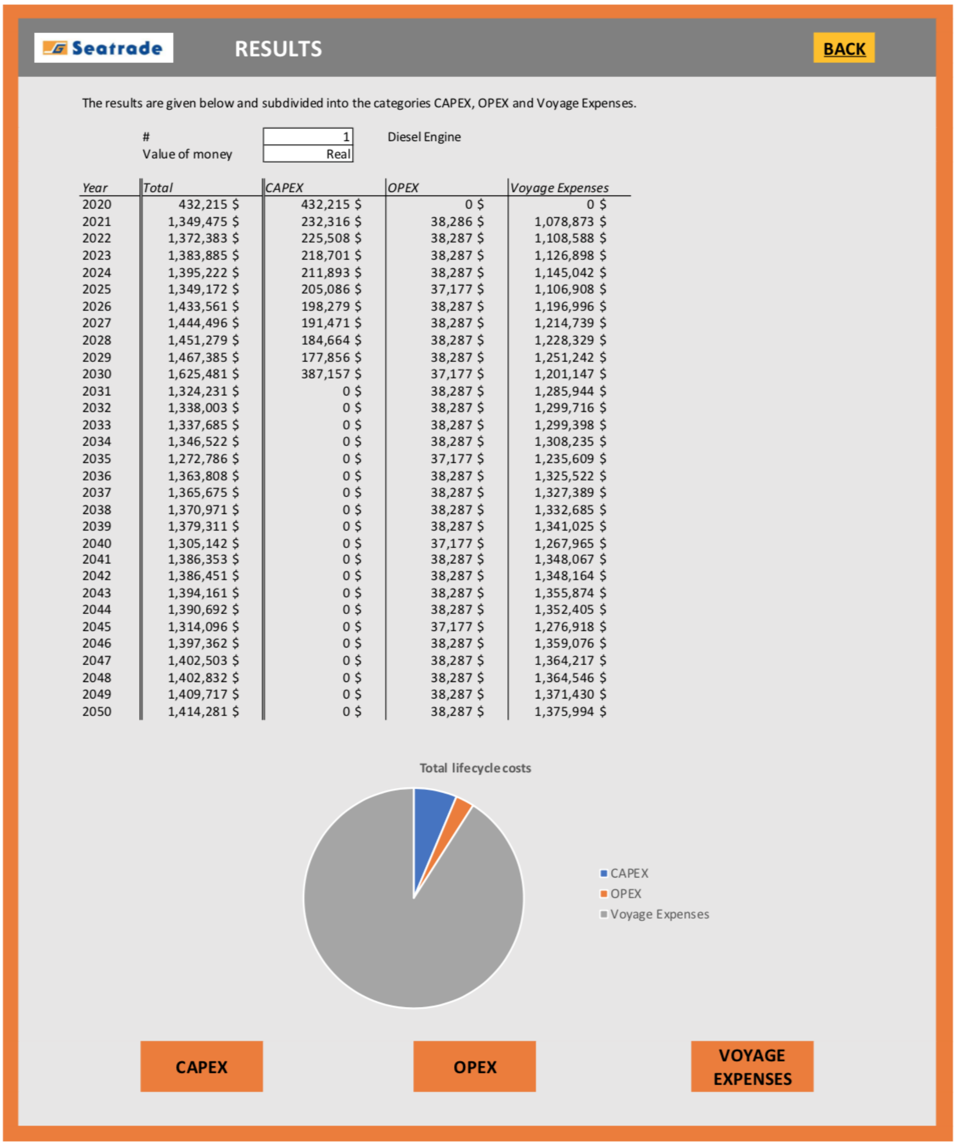
The graph below gives a graphical representation of the results of the NPV analysis.

Below, an evaluation of the net present life-cycle costs is given.

#	*Net present costs*		*Rank*
1	21.78	M$	4
2	23.54	M$	6
3	19.82	M$	1
4	22.51	M$	5
5			
6	21.42	M$	3
7	20.52	M$	2
8			
9	38.52	M$	7
10	39.18	M$	8
11	39.68	M$	9
12	40.35	M$	10
13			

Figure B.18: Tool, NPV analysis

In Figure B.19, the total results of the calculation are given. The costs that are displayed can be shown as nominal or discounted costs. At the bottom of the page, three buttons are shown that are linked to a breakdown of the results into CAPEX, OPEX and voyage expenses, as shown in Figures B.20, B.24 and B.28. A further breakdown of CAPEX into parameters related to engines, abatement techniques and financing is given in Figures B.21, B.22 and B.23. A further breakdown of OPEX into parameters related to engines, fuels and abatement techniques is given in Figure B.25, B.26 and B.27. A further breakdown of voyage expenses into operational areas is given in B.29.

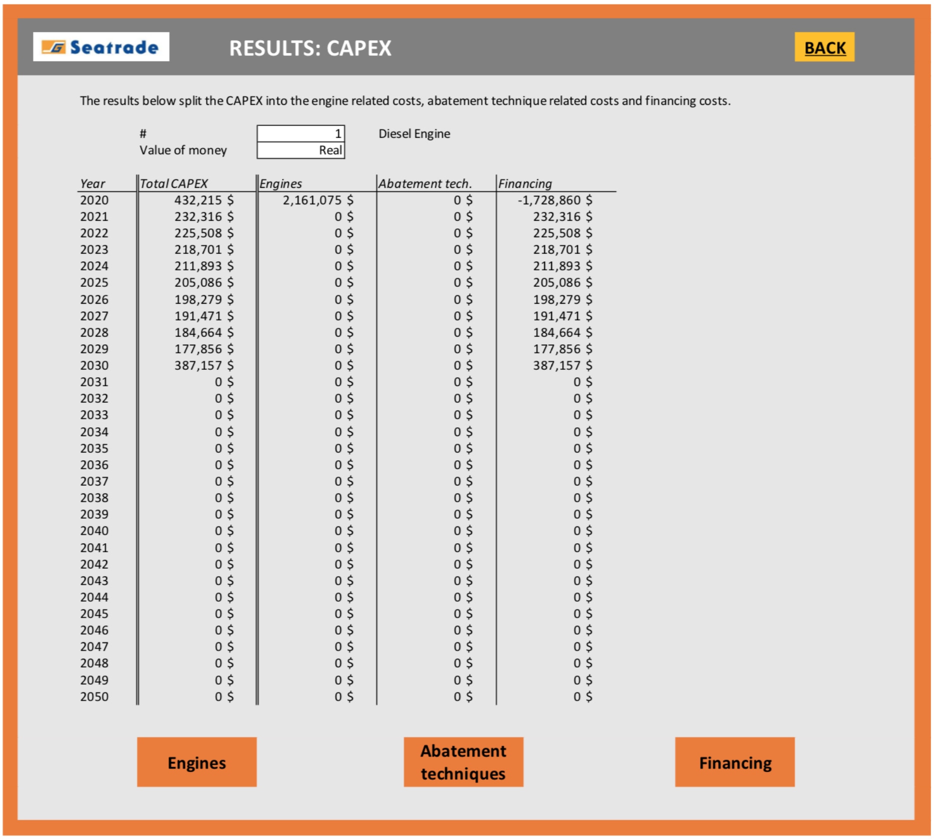


The results are given below and subdivided into the categories CAPEX, OPEX and Voyage Expenses.

1 Diesel Engine
Value of money Real

Year	*Total*	*CAPEX*	*OPEX*	*Voyage Expenses*
2020	432,215 $	432,215 $	0 $	0 $
2021	1,349,475 $	232,316 $	38,286 $	1,078,873 $
2022	1,372,383 $	225,508 $	38,287 $	1,108,588 $
2023	1,383,885 $	218,701 $	38,287 $	1,126,898 $
2024	1,395,222 $	211,893 $	38,287 $	1,145,042 $
2025	1,349,172 $	205,086 $	37,177 $	1,106,908 $
2026	1,433,561 $	198,279 $	38,287 $	1,196,996 $
2027	1,444,496 $	191,471 $	38,287 $	1,214,739 $
2028	1,451,279 $	184,664 $	38,287 $	1,228,329 $
2029	1,467,385 $	177,856 $	38,287 $	1,251,242 $
2030	1,625,481 $	387,157 $	37,177 $	1,201,147 $
2031	1,324,231 $	0 $	38,287 $	1,285,944 $
2032	1,338,003 $	0 $	38,287 $	1,299,716 $
2033	1,337,685 $	0 $	38,287 $	1,299,398 $
2034	1,346,522 $	0 $	38,287 $	1,308,235 $
2035	1,272,786 $	0 $	37,177 $	1,235,609 $
2036	1,363,808 $	0 $	38,287 $	1,325,522 $
2037	1,365,675 $	0 $	38,287 $	1,327,389 $
2038	1,370,971 $	0 $	38,287 $	1,332,685 $
2039	1,379,311 $	0 $	38,287 $	1,341,025 $
2040	1,305,142 $	0 $	37,177 $	1,267,965 $
2041	1,386,353 $	0 $	38,287 $	1,348,067 $
2042	1,386,451 $	0 $	38,287 $	1,348,164 $
2043	1,394,161 $	0 $	38,287 $	1,355,874 $
2044	1,390,692 $	0 $	38,287 $	1,352,405 $
2045	1,314,096 $	0 $	37,177 $	1,276,918 $
2046	1,397,362 $	0 $	38,287 $	1,359,076 $
2047	1,402,503 $	0 $	38,287 $	1,364,217 $
2048	1,402,832 $	0 $	38,287 $	1,364,546 $
2049	1,409,717 $	0 $	38,287 $	1,371,430 $
2050	1,414,281 $	0 $	38,287 $	1,375,994 $

Figure B.19: Tool, total results



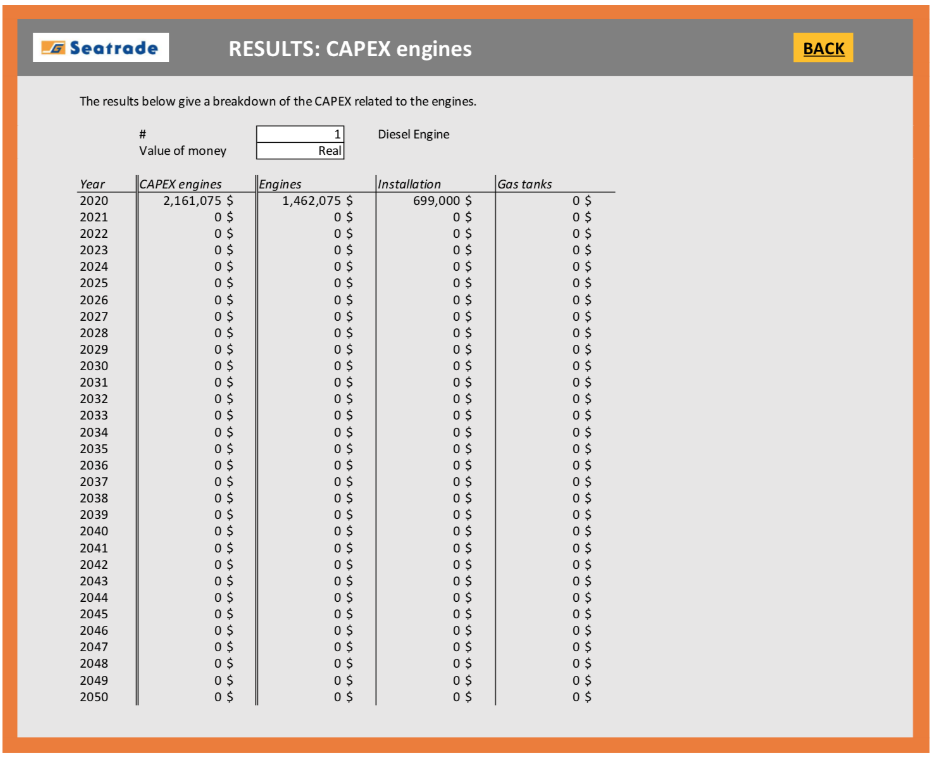
RESULTS: CAPEX

The results below split the CAPEX into the engine related costs, abatement technique related costs and financing costs.

\# 1 Diesel Engine
Value of money Real

Year	*Total CAPEX*	*Engines*	*Abatement tech.*	*Financing*
2020	432,215 $	2,161,075 $	0 $	-1,728,860 $
2021	232,316 $	0 $	0 $	232,316 $
2022	225,508 $	0 $	0 $	225,508 $
2023	218,701 $	0 $	0 $	218,701 $
2024	211,893 $	0 $	0 $	211,893 $
2025	205,086 $	0 $	0 $	205,086 $
2026	198,279 $	0 $	0 $	198,279 $
2027	191,471 $	0 $	0 $	191,471 $
2028	184,664 $	0 $	0 $	184,664 $
2029	177,856 $	0 $	0 $	177,856 $
2030	387,157 $	0 $	0 $	387,157 $
2031	0 $	0 $	0 $	0 $
2032	0 $	0 $	0 $	0 $
2033	0 $	0 $	0 $	0 $
2034	0 $	0 $	0 $	0 $
2035	0 $	0 $	0 $	0 $
2036	0 $	0 $	0 $	0 $
2037	0 $	0 $	0 $	0 $
2038	0 $	0 $	0 $	0 $
2039	0 $	0 $	0 $	0 $
2040	0 $	0 $	0 $	0 $
2041	0 $	0 $	0 $	0 $
2042	0 $	0 $	0 $	0 $
2043	0 $	0 $	0 $	0 $
2044	0 $	0 $	0 $	0 $
2045	0 $	0 $	0 $	0 $
2046	0 $	0 $	0 $	0 $
2047	0 $	0 $	0 $	0 $
2048	0 $	0 $	0 $	0 $
2049	0 $	0 $	0 $	0 $
2050	0 $	0 $	0 $	0 $

Figure B.20: Tool, results CAPEX



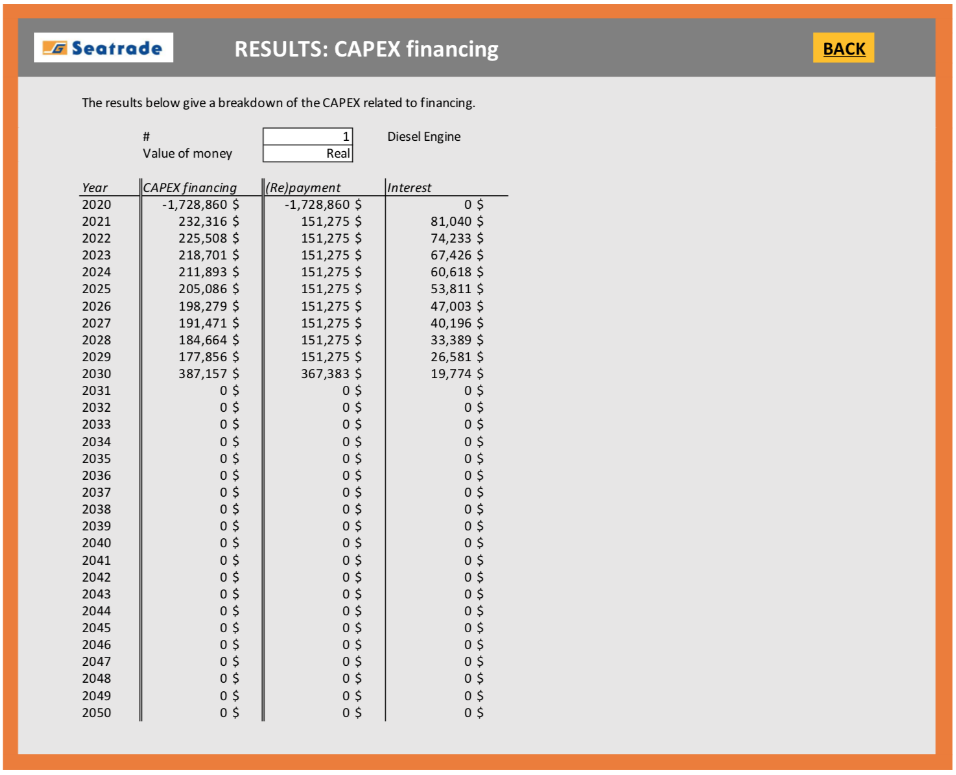
RESULTS: CAPEX engines

The results below give a breakdown of the CAPEX related to the engines.

\# 1 Diesel Engine
Value of money Real

Year	*CAPEX engines*	*Engines*	*Installation*	*Gas tanks*
2020	2,161,075 $	1,462,075 $	699,000 $	0 $
2021	0 $	0 $	0 $	0 $
2022	0 $	0 $	0 $	0 $
2023	0 $	0 $	0 $	0 $
2024	0 $	0 $	0 $	0 $
2025	0 $	0 $	0 $	0 $
2026	0 $	0 $	0 $	0 $
2027	0 $	0 $	0 $	0 $
2028	0 $	0 $	0 $	0 $
2029	0 $	0 $	0 $	0 $
2030	0 $	0 $	0 $	0 $
2031	0 $	0 $	0 $	0 $
2032	0 $	0 $	0 $	0 $
2033	0 $	0 $	0 $	0 $
2034	0 $	0 $	0 $	0 $
2035	0 $	0 $	0 $	0 $
2036	0 $	0 $	0 $	0 $
2037	0 $	0 $	0 $	0 $
2038	0 $	0 $	0 $	0 $
2039	0 $	0 $	0 $	0 $
2040	0 $	0 $	0 $	0 $
2041	0 $	0 $	0 $	0 $
2042	0 $	0 $	0 $	0 $
2043	0 $	0 $	0 $	0 $
2044	0 $	0 $	0 $	0 $
2045	0 $	0 $	0 $	0 $
2046	0 $	0 $	0 $	0 $
2047	0 $	0 $	0 $	0 $
2048	0 $	0 $	0 $	0 $
2049	0 $	0 $	0 $	0 $
2050	0 $	0 $	0 $	0 $

Figure B.21: Tool, results CAPEX engines



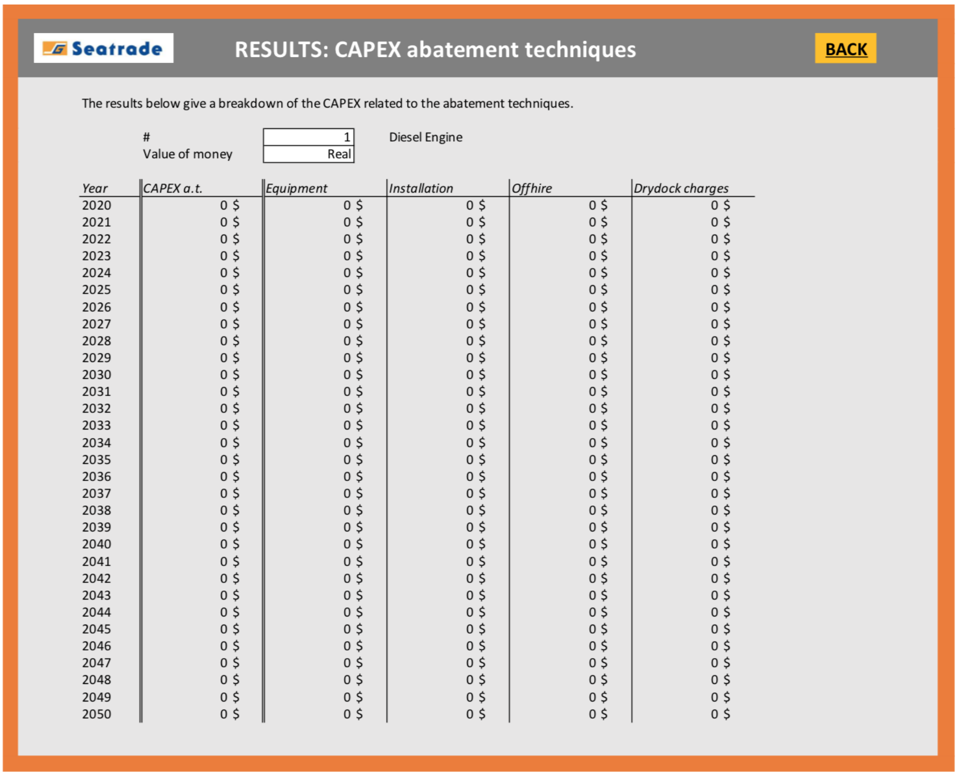
RESULTS: CAPEX financing

The results below give a breakdown of the CAPEX related to financing.

#	1	Diesel Engine
Value of money	Real	

Year	*CAPEX financing*	*(Re)payment*	*Interest*
2020	-1,728,860 $	-1,728,860 $	0 $
2021	232,316 $	151,275 $	81,040 $
2022	225,508 $	151,275 $	74,233 $
2023	218,701 $	151,275 $	67,426 $
2024	211,893 $	151,275 $	60,618 $
2025	205,086 $	151,275 $	53,811 $
2026	198,279 $	151,275 $	47,003 $
2027	191,471 $	151,275 $	40,196 $
2028	184,664 $	151,275 $	33,389 $
2029	177,856 $	151,275 $	26,581 $
2030	387,157 $	367,383 $	19,774 $
2031	0 $	0 $	0 $
2032	0 $	0 $	0 $
2033	0 $	0 $	0 $
2034	0 $	0 $	0 $
2035	0 $	0 $	0 $
2036	0 $	0 $	0 $
2037	0 $	0 $	0 $
2038	0 $	0 $	0 $
2039	0 $	0 $	0 $
2040	0 $	0 $	0 $
2041	0 $	0 $	0 $
2042	0 $	0 $	0 $
2043	0 $	0 $	0 $
2044	0 $	0 $	0 $
2045	0 $	0 $	0 $
2046	0 $	0 $	0 $
2047	0 $	0 $	0 $
2048	0 $	0 $	0 $
2049	0 $	0 $	0 $
2050	0 $	0 $	0 $

Figure B.22: Tool, results CAPEX finance



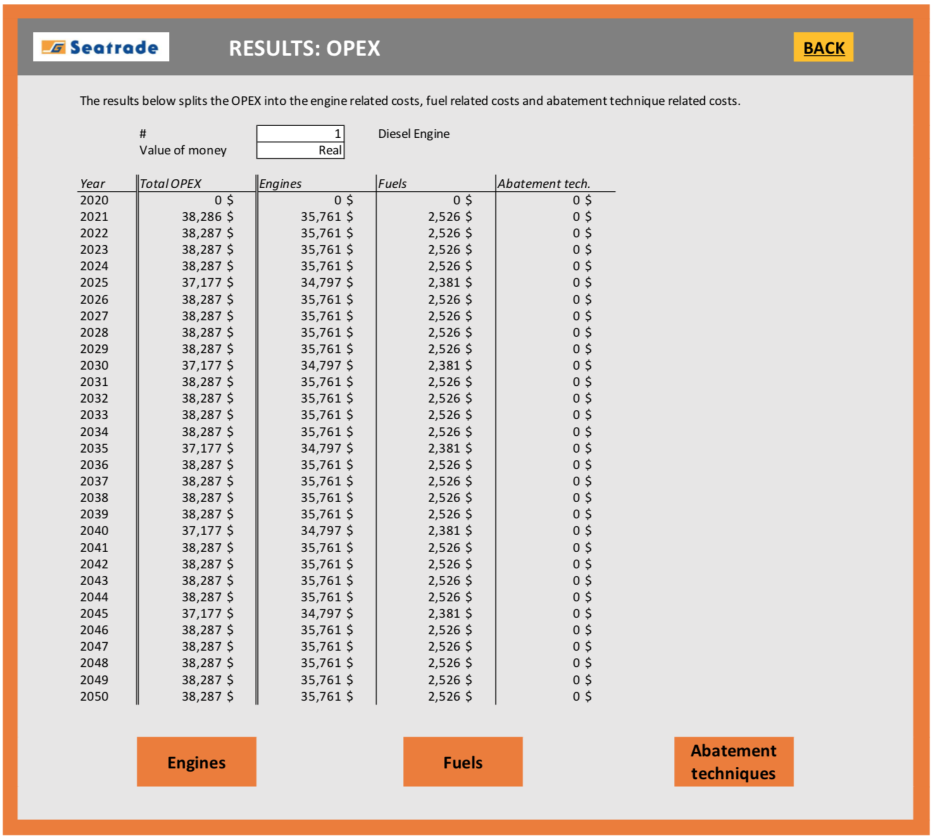
RESULTS: CAPEX abatement techniques

The results below give a breakdown of the CAPEX related to the abatement techniques.

#	1	Diesel Engine
Value of money	Real	

Year	*CAPEX a.t.*	*Equipment*	*Installation*	*Offhire*	*Drydock charges*
2020	0 $	0 $	0 $	0 $	0 $
2021	0 $	0 $	0 $	0 $	0 $
2022	0 $	0 $	0 $	0 $	0 $
2023	0 $	0 $	0 $	0 $	0 $
2024	0 $	0 $	0 $	0 $	0 $
2025	0 $	0 $	0 $	0 $	0 $
2026	0 $	0 $	0 $	0 $	0 $
2027	0 $	0 $	0 $	0 $	0 $
2028	0 $	0 $	0 $	0 $	0 $
2029	0 $	0 $	0 $	0 $	0 $
2030	0 $	0 $	0 $	0 $	0 $
2031	0 $	0 $	0 $	0 $	0 $
2032	0 $	0 $	0 $	0 $	0 $
2033	0 $	0 $	0 $	0 $	0 $
2034	0 $	0 $	0 $	0 $	0 $
2035	0 $	0 $	0 $	0 $	0 $
2036	0 $	0 $	0 $	0 $	0 $
2037	0 $	0 $	0 $	0 $	0 $
2038	0 $	0 $	0 $	0 $	0 $
2039	0 $	0 $	0 $	0 $	0 $
2040	0 $	0 $	0 $	0 $	0 $
2041	0 $	0 $	0 $	0 $	0 $
2042	0 $	0 $	0 $	0 $	0 $
2043	0 $	0 $	0 $	0 $	0 $
2044	0 $	0 $	0 $	0 $	0 $
2045	0 $	0 $	0 $	0 $	0 $
2046	0 $	0 $	0 $	0 $	0 $
2047	0 $	0 $	0 $	0 $	0 $
2048	0 $	0 $	0 $	0 $	0 $
2049	0 $	0 $	0 $	0 $	0 $
2050	0 $	0 $	0 $	0 $	0 $

Figure B.23: Tool, results CAPEX abatement techniques

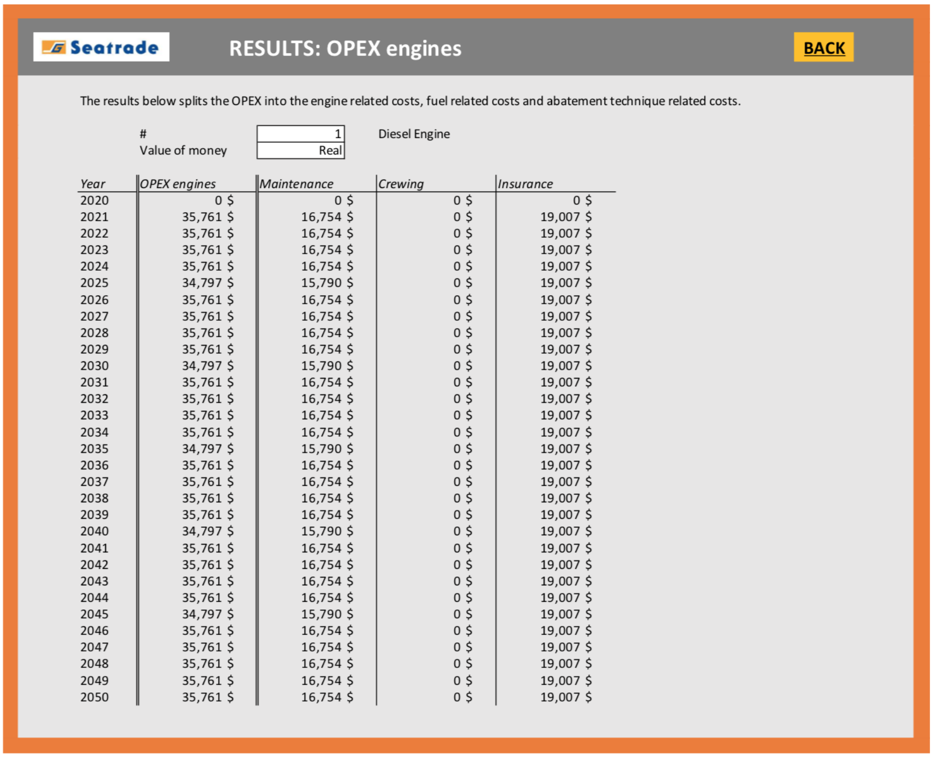


The results below splits the OPEX into the engine related costs, fuel related costs and abatement technique related costs.

1 Diesel Engine
Value of money Real

Year	Total OPEX	Engines	Fuels	Abatement tech.
2020	0 $	0 $	0 $	0 $
2021	38,286 $	35,761 $	2,526 $	0 $
2022	38,287 $	35,761 $	2,526 $	0 $
2023	38,287 $	35,761 $	2,526 $	0 $
2024	38,287 $	35,761 $	2,526 $	0 $
2025	37,177 $	34,797 $	2,381 $	0 $
2026	38,287 $	35,761 $	2,526 $	0 $
2027	38,287 $	35,761 $	2,526 $	0 $
2028	38,287 $	35,761 $	2,526 $	0 $
2029	38,287 $	35,761 $	2,526 $	0 $
2030	37,177 $	34,797 $	2,381 $	0 $
2031	38,287 $	35,761 $	2,526 $	0 $
2032	38,287 $	35,761 $	2,526 $	0 $
2033	38,287 $	35,761 $	2,526 $	0 $
2034	38,287 $	35,761 $	2,526 $	0 $
2035	37,177 $	34,797 $	2,381 $	0 $
2036	38,287 $	35,761 $	2,526 $	0 $
2037	38,287 $	35,761 $	2,526 $	0 $
2038	38,287 $	35,761 $	2,526 $	0 $
2039	38,287 $	35,761 $	2,526 $	0 $
2040	37,177 $	34,797 $	2,381 $	0 $
2041	38,287 $	35,761 $	2,526 $	0 $
2042	38,287 $	35,761 $	2,526 $	0 $
2043	38,287 $	35,761 $	2,526 $	0 $
2044	38,287 $	35,761 $	2,526 $	0 $
2045	37,177 $	34,797 $	2,381 $	0 $
2046	38,287 $	35,761 $	2,526 $	0 $
2047	38,287 $	35,761 $	2,526 $	0 $
2048	38,287 $	35,761 $	2,526 $	0 $
2049	38,287 $	35,761 $	2,526 $	0 $
2050	38,287 $	35,761 $	2,526 $	0 $

Figure B.24: Tool, results OPEX

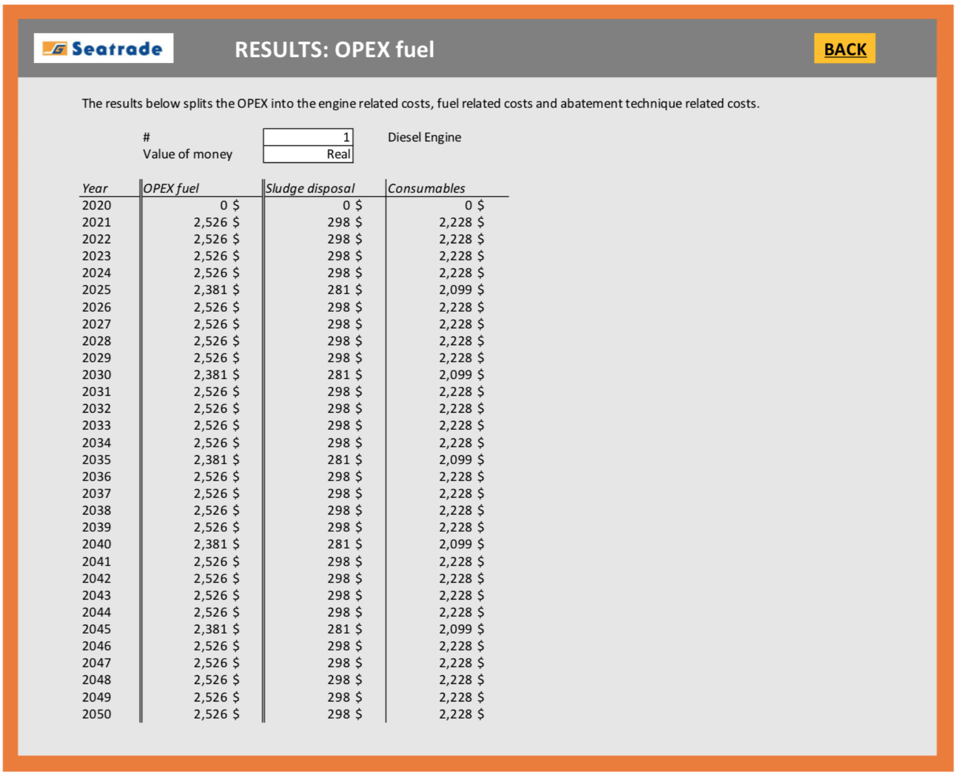


The results below splits the OPEX into the engine related costs, fuel related costs and abatement technique related costs.

1 Diesel Engine
Value of money Real

Year	OPEX engines	Maintenance	Crewing	Insurance
2020	0 $	0 $	0 $	0 $
2021	35,761 $	16,754 $	0 $	19,007 $
2022	35,761 $	16,754 $	0 $	19,007 $
2023	35,761 $	16,754 $	0 $	19,007 $
2024	35,761 $	16,754 $	0 $	19,007 $
2025	34,797 $	15,790 $	0 $	19,007 $
2026	35,761 $	16,754 $	0 $	19,007 $
2027	35,761 $	16,754 $	0 $	19,007 $
2028	35,761 $	16,754 $	0 $	19,007 $
2029	35,761 $	16,754 $	0 $	19,007 $
2030	34,797 $	15,790 $	0 $	19,007 $
2031	35,761 $	16,754 $	0 $	19,007 $
2032	35,761 $	16,754 $	0 $	19,007 $
2033	35,761 $	16,754 $	0 $	19,007 $
2034	35,761 $	16,754 $	0 $	19,007 $
2035	34,797 $	15,790 $	0 $	19,007 $
2036	35,761 $	16,754 $	0 $	19,007 $
2037	35,761 $	16,754 $	0 $	19,007 $
2038	35,761 $	16,754 $	0 $	19,007 $
2039	35,761 $	16,754 $	0 $	19,007 $
2040	34,797 $	15,790 $	0 $	19,007 $
2041	35,761 $	16,754 $	0 $	19,007 $
2042	35,761 $	16,754 $	0 $	19,007 $
2043	35,761 $	16,754 $	0 $	19,007 $
2044	35,761 $	16,754 $	0 $	19,007 $
2045	34,797 $	15,790 $	0 $	19,007 $
2046	35,761 $	16,754 $	0 $	19,007 $
2047	35,761 $	16,754 $	0 $	19,007 $
2048	35,761 $	16,754 $	0 $	19,007 $
2049	35,761 $	16,754 $	0 $	19,007 $
2050	35,761 $	16,754 $	0 $	19,007 $

Figure B.25: Tool, results OPEX engines



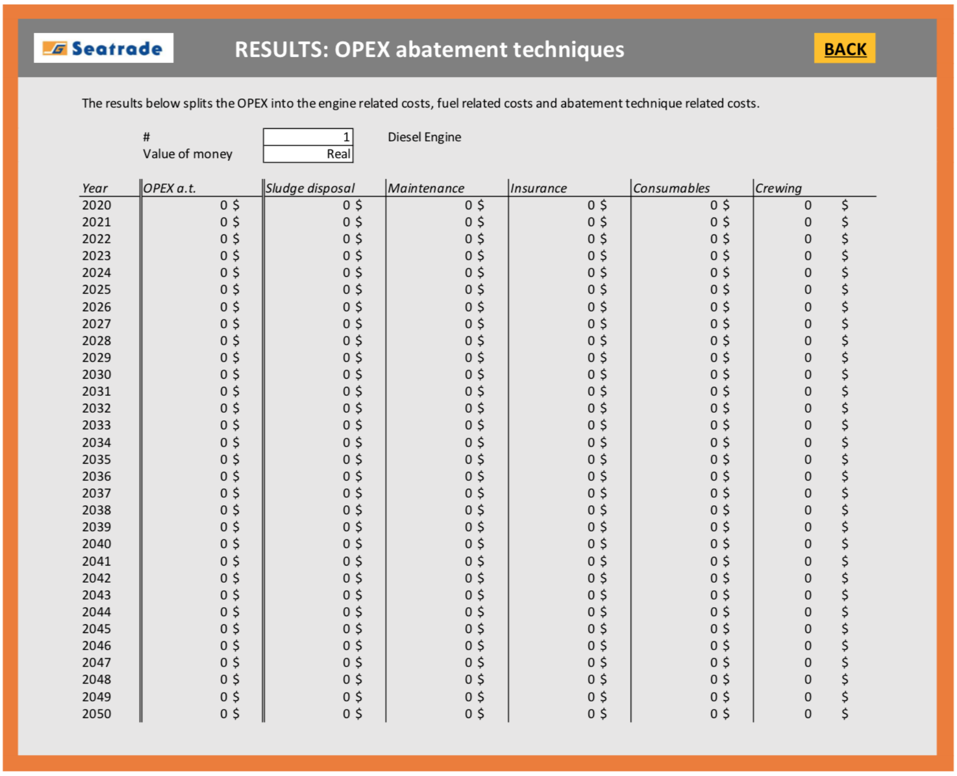
RESULTS: OPEX fuel

The results below splits the OPEX into the engine related costs, fuel related costs and abatement technique related costs.

#	1	Diesel Engine
Value of money	Real	

Year	OPEX fuel	Sludge disposal	Consumables
2020	0 $	0 $	0 $
2021	2,526 $	298 $	2,228 $
2022	2,526 $	298 $	2,228 $
2023	2,526 $	298 $	2,228 $
2024	2,526 $	298 $	2,228 $
2025	2,381 $	281 $	2,099 $
2026	2,526 $	298 $	2,228 $
2027	2,526 $	298 $	2,228 $
2028	2,526 $	298 $	2,228 $
2029	2,526 $	298 $	2,228 $
2030	2,381 $	281 $	2,099 $
2031	2,526 $	298 $	2,228 $
2032	2,526 $	298 $	2,228 $
2033	2,526 $	298 $	2,228 $
2034	2,526 $	298 $	2,228 $
2035	2,381 $	281 $	2,099 $
2036	2,526 $	298 $	2,228 $
2037	2,526 $	298 $	2,228 $
2038	2,526 $	298 $	2,228 $
2039	2,526 $	298 $	2,228 $
2040	2,381 $	281 $	2,099 $
2041	2,526 $	298 $	2,228 $
2042	2,526 $	298 $	2,228 $
2043	2,526 $	298 $	2,228 $
2044	2,526 $	298 $	2,228 $
2045	2,381 $	281 $	2,099 $
2046	2,526 $	298 $	2,228 $
2047	2,526 $	298 $	2,228 $
2048	2,526 $	298 $	2,228 $
2049	2,526 $	298 $	2,228 $
2050	2,526 $	298 $	2,228 $

Figure B.26: Tool, results OPEX fuels



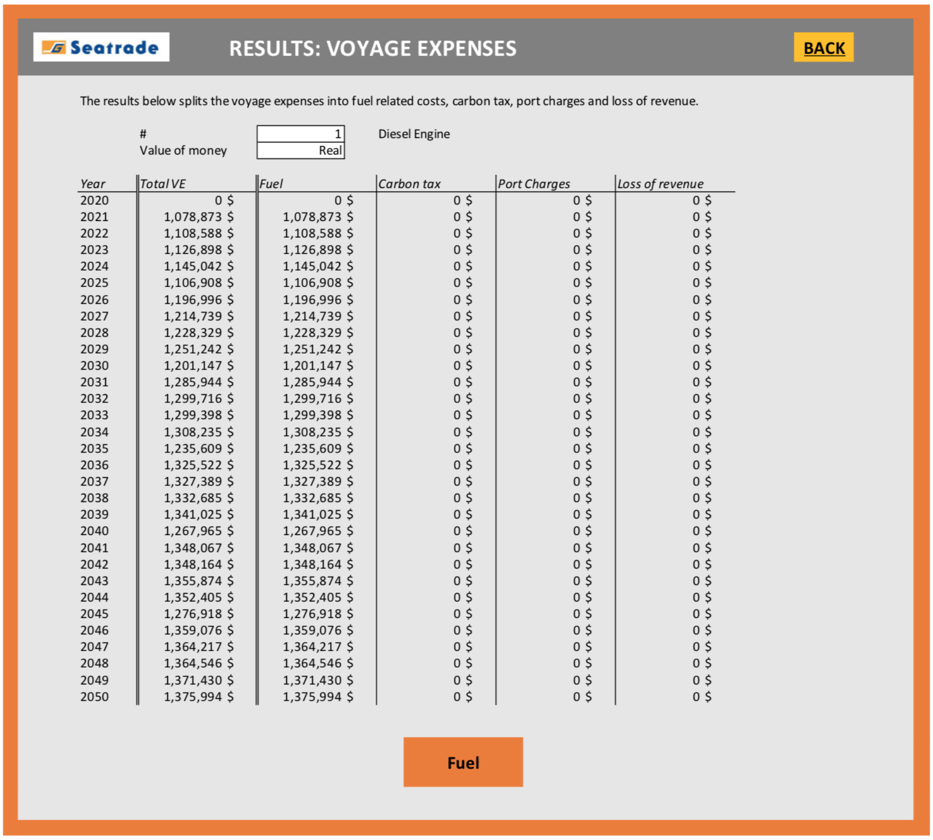
RESULTS: OPEX abatement techniques

The results below splits the OPEX into the engine related costs, fuel related costs and abatement technique related costs.

#	1	Diesel Engine
Value of money	Real	

Year	OPEX a.t.	Sludge disposal	Maintenance	Insurance	Consumables	Crewing
2020	0 $	0 $	0 $	0 $	0 $	0 $
2021	0 $	0 $	0 $	0 $	0 $	0 $
2022	0 $	0 $	0 $	0 $	0 $	0 $
2023	0 $	0 $	0 $	0 $	0 $	0 $
2024	0 $	0 $	0 $	0 $	0 $	0 $
2025	0 $	0 $	0 $	0 $	0 $	0 $
2026	0 $	0 $	0 $	0 $	0 $	0 $
2027	0 $	0 $	0 $	0 $	0 $	0 $
2028	0 $	0 $	0 $	0 $	0 $	0 $
2029	0 $	0 $	0 $	0 $	0 $	0 $
2030	0 $	0 $	0 $	0 $	0 $	0 $
2031	0 $	0 $	0 $	0 $	0 $	0 $
2032	0 $	0 $	0 $	0 $	0 $	0 $
2033	0 $	0 $	0 $	0 $	0 $	0 $
2034	0 $	0 $	0 $	0 $	0 $	0 $
2035	0 $	0 $	0 $	0 $	0 $	0 $
2036	0 $	0 $	0 $	0 $	0 $	0 $
2037	0 $	0 $	0 $	0 $	0 $	0 $
2038	0 $	0 $	0 $	0 $	0 $	0 $
2039	0 $	0 $	0 $	0 $	0 $	0 $
2040	0 $	0 $	0 $	0 $	0 $	0 $
2041	0 $	0 $	0 $	0 $	0 $	0 $
2042	0 $	0 $	0 $	0 $	0 $	0 $
2043	0 $	0 $	0 $	0 $	0 $	0 $
2044	0 $	0 $	0 $	0 $	0 $	0 $
2045	0 $	0 $	0 $	0 $	0 $	0 $
2046	0 $	0 $	0 $	0 $	0 $	0 $
2047	0 $	0 $	0 $	0 $	0 $	0 $
2048	0 $	0 $	0 $	0 $	0 $	0 $
2049	0 $	0 $	0 $	0 $	0 $	0 $
2050	0 $	0 $	0 $	0 $	0 $	0 $

Figure B.27: Tool, results OPEX abatement techniques



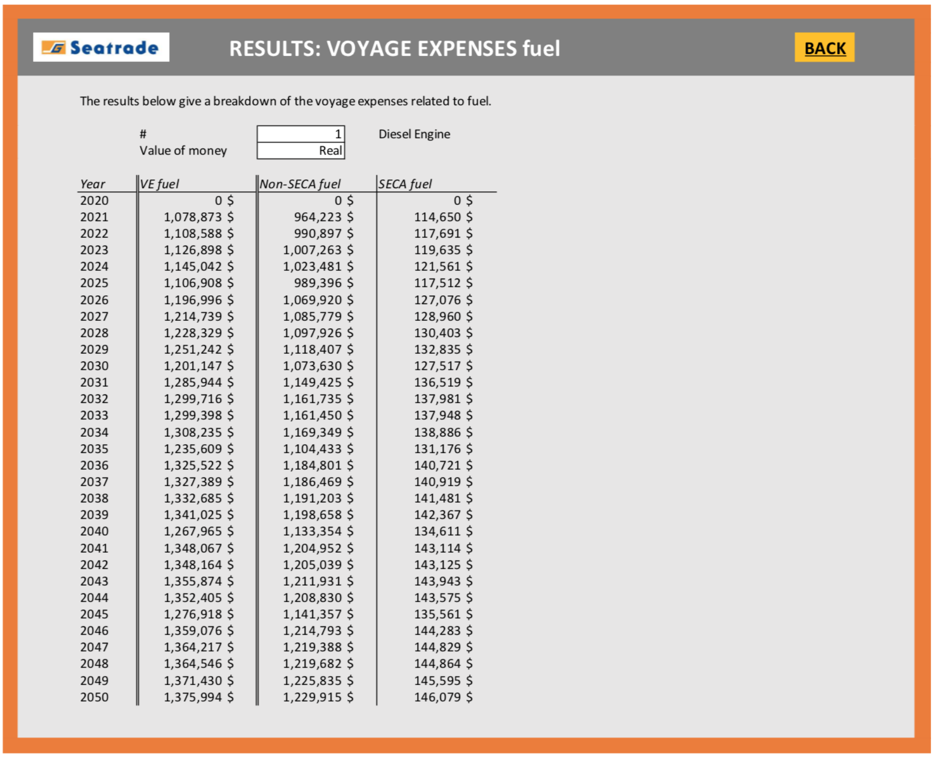
RESULTS: VOYAGE EXPENSES

The results below splits the voyage expenses into fuel related costs, carbon tax, port charges and loss of revenue.

1 Diesel Engine
Value of money Real

Year	*Total VE*	*Fuel*	*Carbon tax*	*Port Charges*	*Loss of revenue*
2020	0 $	0 $	0 $	0 $	0 $
2021	1,078,873 $	1,078,873 $	0 $	0 $	0 $
2022	1,108,588 $	1,108,588 $	0 $	0 $	0 $
2023	1,126,898 $	1,126,898 $	0 $	0 $	0 $
2024	1,145,042 $	1,145,042 $	0 $	0 $	0 $
2025	1,106,908 $	1,106,908 $	0 $	0 $	0 $
2026	1,196,996 $	1,196,996 $	0 $	0 $	0 $
2027	1,214,739 $	1,214,739 $	0 $	0 $	0 $
2028	1,228,329 $	1,228,329 $	0 $	0 $	0 $
2029	1,251,242 $	1,251,242 $	0 $	0 $	0 $
2030	1,201,147 $	1,201,147 $	0 $	0 $	0 $
2031	1,285,944 $	1,285,944 $	0 $	0 $	0 $
2032	1,299,716 $	1,299,716 $	0 $	0 $	0 $
2033	1,299,398 $	1,299,398 $	0 $	0 $	0 $
2034	1,308,235 $	1,308,235 $	0 $	0 $	0 $
2035	1,235,609 $	1,235,609 $	0 $	0 $	0 $
2036	1,325,522 $	1,325,522 $	0 $	0 $	0 $
2037	1,327,389 $	1,327,389 $	0 $	0 $	0 $
2038	1,332,685 $	1,332,685 $	0 $	0 $	0 $
2039	1,341,025 $	1,341,025 $	0 $	0 $	0 $
2040	1,267,965 $	1,267,965 $	0 $	0 $	0 $
2041	1,348,067 $	1,348,067 $	0 $	0 $	0 $
2042	1,348,164 $	1,348,164 $	0 $	0 $	0 $
2043	1,355,874 $	1,355,874 $	0 $	0 $	0 $
2044	1,352,405 $	1,352,405 $	0 $	0 $	0 $
2045	1,276,918 $	1,276,918 $	0 $	0 $	0 $
2046	1,359,076 $	1,359,076 $	0 $	0 $	0 $
2047	1,364,217 $	1,364,217 $	0 $	0 $	0 $
2048	1,364,546 $	1,364,546 $	0 $	0 $	0 $
2049	1,371,430 $	1,371,430 $	0 $	0 $	0 $
2050	1,375,994 $	1,375,994 $	0 $	0 $	0 $

Figure B.28: Tool, results VE



RESULTS: VOYAGE EXPENSES fuel

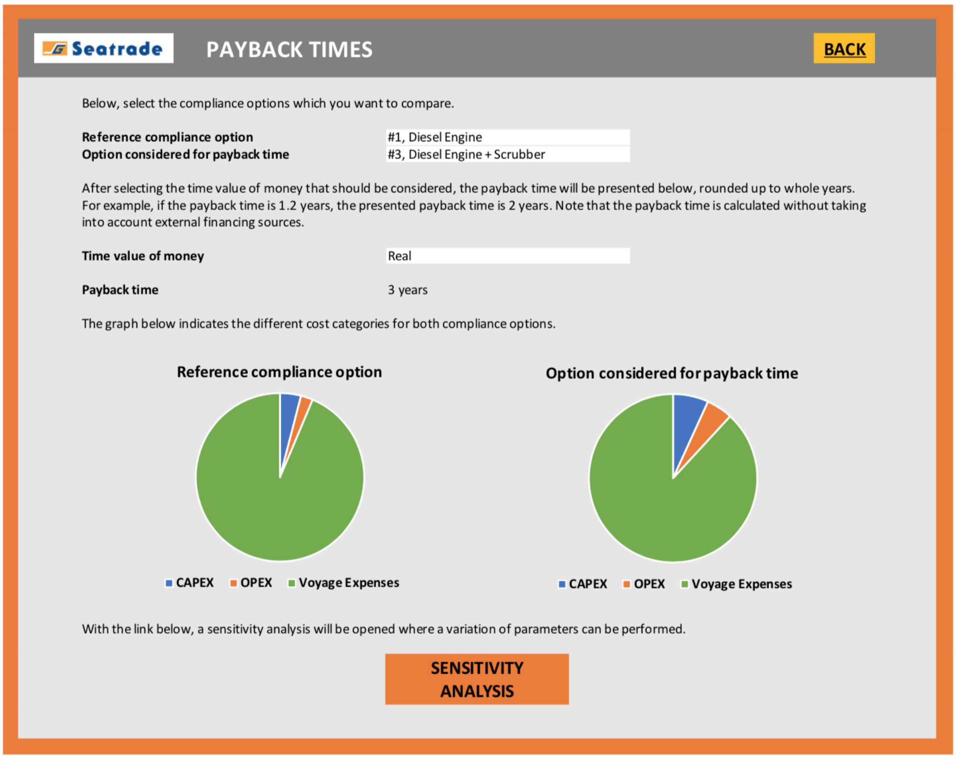
The results below give a breakdown of the voyage expenses related to fuel.

1 Diesel Engine
Value of money Real

Year	*VE fuel*	*Non-SECA fuel*	*SECA fuel*
2020	0 $	0 $	0 $
2021	1,078,873 $	964,223 $	114,650 $
2022	1,108,588 $	990,897 $	117,691 $
2023	1,126,898 $	1,007,263 $	119,635 $
2024	1,145,042 $	1,023,481 $	121,561 $
2025	1,106,908 $	989,396 $	117,512 $
2026	1,196,996 $	1,069,920 $	127,076 $
2027	1,214,739 $	1,085,779 $	128,960 $
2028	1,228,329 $	1,097,926 $	130,403 $
2029	1,251,242 $	1,118,407 $	132,835 $
2030	1,201,147 $	1,073,630 $	127,517 $
2031	1,285,944 $	1,149,425 $	136,519 $
2032	1,299,716 $	1,161,735 $	137,981 $
2033	1,299,398 $	1,161,450 $	137,948 $
2034	1,308,235 $	1,169,349 $	138,886 $
2035	1,235,609 $	1,104,433 $	131,176 $
2036	1,325,522 $	1,184,801 $	140,721 $
2037	1,327,389 $	1,186,469 $	140,919 $
2038	1,332,685 $	1,191,203 $	141,481 $
2039	1,341,025 $	1,198,658 $	142,367 $
2040	1,267,965 $	1,133,354 $	134,611 $
2041	1,348,067 $	1,204,952 $	143,114 $
2042	1,348,164 $	1,205,039 $	143,125 $
2043	1,355,874 $	1,211,931 $	143,943 $
2044	1,352,405 $	1,208,830 $	143,575 $
2045	1,276,918 $	1,141,357 $	135,561 $
2046	1,359,076 $	1,214,793 $	144,283 $
2047	1,364,217 $	1,219,388 $	144,829 $
2048	1,364,546 $	1,219,682 $	144,864 $
2049	1,371,430 $	1,225,835 $	145,595 $
2050	1,375,994 $	1,229,915 $	146,079 $

Figure B.29: Tool, results VE fuels

In Figure B.30, the payback times between two compliance options can be shown. Two compliance options can be selected and also the time value of money can be switched between real and discounted. The link on the bottom of the pages opens a screen where a sensitivity analysis on the payback periods can be conducted.



Below, select the compliance options which you want to compare.

Reference compliance option #1, Diesel Engine
Option considered for payback time #3, Diesel Engine + Scrubber

After selecting the time value of money that should be considered, the payback time will be presented below, rounded up to whole years. For example, if the payback time is 1.2 years, the presented payback time is 2 years. Note that the payback time is calculated without taking into account external financing sources.

Time value of money Real

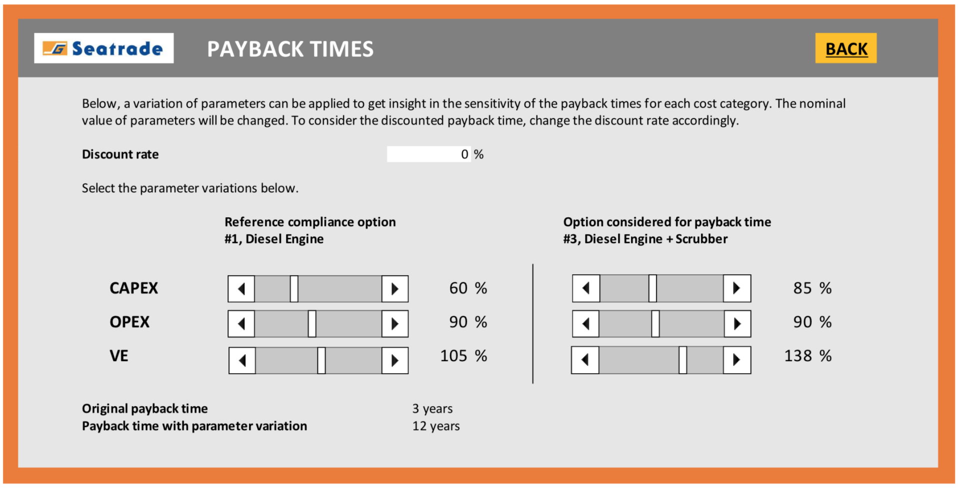
Payback time 3 years

The graph below indicates the different cost categories for both compliance options.

With the link below, a sensitivity analysis will be opened where a variation of parameters can be performed.

Figure B.30: Tool, payback times

In Figure B.31, a sensitivity analysis can be conducted to discover the influences of the CAPEX, OPEX and VE on the payback periods. The compliance options that are selected in Figure B.30 will be used. Of both compliance options, the parameters can be changed.



Below, a variation of parameters can be applied to get insight in the sensitivity of the payback times for each cost category. The nominal value of parameters will be changed. To consider the discounted payback time, change the discount rate accordingly.

Discount rate 0 %

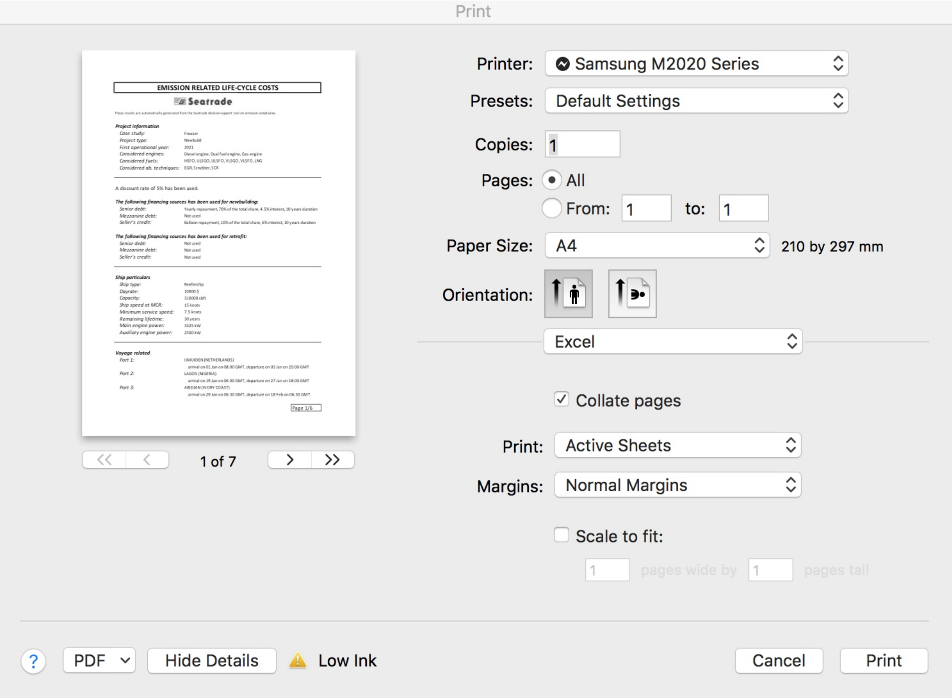
Select the parameter variations below.

	Reference compliance option **#1, Diesel Engine**	**Option considered for payback time** **#3, Diesel Engine + Scrubber**
CAPEX	60 %	85 %
OPEX	90 %	90 %
VE	105 %	138 %

Original payback time 3 years
Payback time with parameter variation 12 years

Figure B.31: Tool, sensitivity of payback times

If pushing the 'Print summary' button in the results menu that is shown in Figure B.14, a print dialog screen will be opened to print a summary of the input data and results of the particular case study. An example of a print dialog screen is given in B.32 but might vary per computer system.



Print

EMISSION RELATED LIFE-CYCLE COSTS

Seatrade

These results are automatically generated from the Seatrade decision-support tool on emission compliance.

Project information

Case study: Freezer
Project type: Newbuild
First operational year: 2021
Considered engines: Diesel engine, Dual fuel engine, Gas engine
Considered fuels: HSFO, ULSGO, ULSFO, VLSGO, VLSFO, LNG
Considered ab. techniques: EGR, Scrubber, SCR

A discount rate of 5% has been used.

The following financing sources has been used for newbuilding:

Senior debt: Yearly repayment, 70% of the total share, 4.5% interest, 10 years duration
Mezzanine debt: Not used
Seller's credit: Balloon repayment, 10% of the total share, 6% interest, 10 years duration

The following financing sources has been used for retrofit:

Senior debt: Not used
Mezzanine debt: Not used
Seller's credit: Not used

Ship particulars

Ship type: Reefership
Dayrate: 10000 $
Capacity: 310000 cbft
Ship speed at MCR: 15 knots
Minimum service speed: 7.5 knots
Remaining lifetime: 30 years
Main engine power: 3325 kW
Auxiliary engine power: 2500 kW

Voyage related

Port 1: IJMUIDEN (NETHERLANDS)
arrival on 01 Jan on 08:00 GMT, departure on 05 Jan on 20:00 GMT
Port 2: LAGOS (NIGERIA)
arrival on 19 Jan on 06:00 GMT, departure on 27 Jan on 18:00 GMT
Port 3: ABIDJAN (IVORY COAST)
arrival on 29 Jan on 06:30 GMT, departure on 18 Feb on 06:30 GMT

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Printer: Samsung M2020 Series
Presets: Default Settings
Copies: 1
Pages: ● All ○ From: 1 to: 1
Paper Size: A4 210 by 297 mm
Orientation:
Excel
☑ Collate pages
Print: Active Sheets
Margins: Normal Margins
☐ Scale to fit: 1 pages wide by 1 pages tall

Figure B.32: Tool, print summary

C

Case study 1: input

This appendix gives the declaration of the input data for the first case study, which is subdivided in the categories that are used in the tool. A list of input parameters related to general project information and which options to consider is given in Table C.1.

Table C.1: Case study 1, input general project data

Parameter	***Value***	***Unit***
Project name	*Freezer*	-
First operational year	*2021*	-
Diesel Engine	*YES*	-
Dual Fuel Engine	*YES*	-
Gas Engine	*YES*	-
Fuel Cells	*NO*	-
HSFO	*YES*	-
ULSGO	*YES*	-
ULSFO	*YES*	-
VLSGO	*YES*	-
VLSFO	*YES*	-
LNG	*YES*	-
Bio-diesel	*NO*	-
Bio-LNG	*NO*	-
Hydrogen	*NO*	-
EGR	*YES*	-
Scrubber	*YES*	-
SCR	*YES*	-
WHRS	*NO*	-

A list of input parameters related to financing is given in Table C.2. As no retrofit is considered at all, those input values are left blank and are not listed below.

Table C.2: Case study 1, input financing data

Parameter	***Value***	***Unit***
Discount rate	*5*	%
Senior debt, repayment	*Yearly*	-
Senior debt, share	*70*	%
Senior debt, interest rate	*4.5*	%
Senior debt, tenor	*10*	years
Mezzanine debt, repayment	*No*	-
Mezzanine debt, share	*0*	%

Parameter	***Value***	***Unit***
Mezzanine debt, interest rate	*0*	%
Mezzanine debt, tenor	*0*	years
Seller's credit, repayment	*Balloon*	-
Seller's credit, share	*10*	%
Seller's credit, interest rate	*6*	%
Seller's credit, tenor	*10*	years

A list of input parameters related to ship specific data is given in Table C.3.

Table C.3: Case study 1, input ship data

Parameter	***Value***	***Unit***
Ship type	*Reefership*	-
Propeller type	*Fixed Pitch Propeller*	-
Dayrate	*10,000*	$
Cargo capacity	*310,000*	cbft
Ship speed at MCR	*15.0*	knots
Minimum service speed	*7.5*	knots
Remaining commercial lifetime	*30*	years
Main engine power	*3325*	kW
Auxiliary engine power	*625*	kW
Number of auxiliary engines	*4*	-
Drydock rate	*4000*	$/day
Original drydock period	*21*	days
First drydock year	*2025*	-
Crew responsible for safety duties	9	persons
Wages of crew responsible for safety duties	*2300*	$/month
Crew responsible for fuel handling	*4*	persons
Wages of crew responsible for fuel handling	*5785*	$/month
Insurance rate	*1.3*	%
EEDI reference parameter a	*227.01*	-
EEDI reference parameter b	*8140*	DWT
EEDI reference parameter c	*0.244*	-

A list of input parameters related to voyage data is given in Table C.4. The voyage schedule is separately given in Table C.5.

Table C.4: Case study 1, input voyage data

Parameter	***Value***	***Unit***
Required tank volume	*1270*	m^3
Simultaneous operations	*No*	-
Bunker time for low-flashpoint fuels	2	hours
Compensation stretch 1	*IJmuiden - Lagos*	-
Compensation stretch 2	-	-
Auxiliary power required in port	*645*	kW
Auxiliary power required at sea	*518*	kW
Sludge disposal costs	*30*	$/T
Carbon tax	*0*	$/T
Average container weight	*15*	T

Table C.5: Case study 1, input voyage schedule

#	***Port***	***Arrival date***	***Arrival time***	***Departure date***	***Departure time***
1	IJmuiden (Netherlands)	01-Jan	08:00	05-Jan	20:00
2	Lagos (Nigeria)	19-Jan	06:00	27-Jan	18:00
3	Abidjan (Ivory Coast)	29-Jan	06:30	18-Feb	06:30
4	Puebla d. Caraminal (Spain)	27-Feb	12:00	22-Mar	12:00
5	IJmuiden (Netherlands)	25-Mar	11:00	29-Mar	23:00

A list of input parameters related to the engines is given in Table C.6. As fuel cells will be not considered at all, those input values are left blank and are not listed below.

Table C.6: Case study 1, input engine data

Parameter	***Value***	***Unit***
DE, engine costs	*251.0*	$/kW
DE, gas tank costs	*0.0*	$/m^3
DE, engineering costs	*120.0*	$/kW
DE, maintenance costs	*1.5*	$/MWh
DE, add. volume required	*0*	ft^3
DE, ME rated speed	*127.0*	rpm
DE, ME SFC at MCR	*175.0*	g/kWh
DE, reference LHV	*42.7*	MJ/kg
DE, AE rated speed	*720*	rpm
DE, AE SFC at MCR	*187.0*	g/kWh
DF, engine costs	*396.7*	$/kW
DF, gas tank costs	*7205.1*	\$/m^{3}
DF, engineering costs	*120.0*	$/kW
DF, maintenance costs	*1.7*	$/MWh
DF, add. volume required	*44850*	ft^{3}
DF, ME rated speed	*127.0*	rpm
DF, ME SFC at MCR	*174.0*	g/kWh
DF, reference LHV	*42.7*	MJ/kg
DF, AE rated speed	*720*	rpm
DF, AE SFC at MCR	*186.0*	g/kWh
GE, engine costs	*388.0*	$/kW
GE, gas tank costs	*7205.1*	$/m^3
GE, engineering costs	*120.0*	$/kW
GE, maintenance costs	*1.0*	$/MWh
GE, add. volume required	*44850*	ft^{3}
GE, ME rated speed	*1500*	rpm
GE, ME SFC at MCR	*181.4*	g/kWh
GE, reference LHV	*42.7*	MJ/kg
GE, AE rated speed	*1500*	rpm
GE, AE SFC at MCR	*181.4*	g/kWh

A list of input parameters related to the fuels is given in Table C.7. As bio-diesel, bio-LNG and hydrogen will be not considered at all, those input values are left blank and are not listed below. The fuel prices that are used are separately listed in Table C.8 and given in $/T.

Table C.7: Case study 1, input fuel data

Parameter	***Value***	***Unit***
HSFO, LHV	*40.0*	MJ/kg
HSFO, carbon content	*0.849*	%
HSFO, consumables	*0.61*	$/MWh
HSFO, sludge production	*1.5*	%

Parameter	***Value***	***Unit***
HSFO, SOx reduction potential	*0*	%
HSFO, NOx reduction potential	*0*	%
HSFO, CO2 reduction potential	*0*	%
HSFO, PM reduction potential	*0*	%
ULSGO, LHV	*42.7*	MJ/kg
ULSGO, carbon content	*0.874*	%
ULSGO, consumables	*1.12*	$/MWh
ULSGO, sludge production	*0.5*	%
ULSGO, SOx reduction potential	*97*	%
ULSGO, NOx reduction potential	*0*	%
ULSGO, CO2 reduction potential	*0*	%
ULSGO, PM reduction potential	*60*	%
ULSFO, LHV	*40.0*	MJ/kg
ULSFO, carbon content	*0.849*	%
ULSFO, consumables	*0.70*	$/MWh
ULSFO, sludge production	*1.0*	%
ULSFO, SOx reduction potential	*97*	%
ULSFO, NOx reduction potential	*0*	%
ULSFO, CO2 reduction potential	*0*	%
ULSFO, PM reduction potential	*0*	%
VLSGO, LHV	*42.7*	MJ/kg
VLSGO, carbon content	*0.847*	%
VLSGO, consumables	*1.12*	$/MWh
VLSGO, sludge production	*0.5*	%
VLSGO, SOx reduction potential	*86*	%
VLSGO, NOx reduction potential	*0*	%
VLSGO, CO2 reduction potential	*0*	%
VLSGO, PM reduction potential	*60*	%
VLSFO, LHV	*40.0*	MJ/kg
VLSFO, carbon content	*0.849*	%
VLSFO, consumables	*0.70*	$/MWh
VLSFO, sludge production	*1.1*	%
VLSFO, SOx reduction potential	*86*	%
VLSFO, NOx reduction potential	*0*	%
VLSFO, CO2 reduction potential	*0*	%
VLSFO, PM reduction potential	*0*	%
LNG, LHV	*49.2*	MJ/kg
LNG, carbon content	*0.750*	%
LNG, consumables	*1.06*	$/MWh
LNG, sludge production	*0.0*	%
LNG, SOx reduction potential	*100*	%
LNG, NOx reduction potential	*90*	%
LNG, CO2 reduction potential	*20*	%
LNG, PM reduction potential	*99*	%

Table C.8: Case study 1, fuel price projection ($/T)

Year	***HSFO***	***ULSGO***	***ULSFO***	***VLSGO***	***VLSFO***	***LNG (EU)***
2021	345.4	567.2	541.7	539.6	515.4	507.1
2022	354.9	582.8	556.6	554.5	529.6	524.1
2023	360.8	592.5	565.8	563.7	538.4	538.6
2024	366.6	602.0	574.9	572.7	547.0	559.2
2025	376.0	617.5	589.7	587.5	561.1	576.2

Year	***HSFO***	***ULSGO***	***ULSFO***	***VLSGO***	***VLSFO***	***LNG (EU)***
2026	383.2	629.3	601.0	598.7	571.9	589.6
2027	388.9	638.7	609.9	607.6	580.3	599.3
2028	393.3	645.8	616.7	614.4	586.8	609.1
2029	400.6	657.8	628.2	625.9	597.8	622.5
2030	408.1	670.0	639.9	637.5	608.9	632.2
2031	411.7	676.1	645.7	643.2	614.4	634.8
2032	416.1	683.3	652.6	650.1	620.9	637.4
2033	416.0	683.2	652.4	649.9	620.8	640.0
2034	418.9	687.8	656.9	654.4	625.0	642.6
2035	419.8	689.3	658.3	655.8	626.3	645.2
2036	424.4	696.9	655.5	663.0	633.3	647.8
2037	425.0	697.9	656.5	663.9	634.2	650.4
2038	426.7	700.7	669.1	666.6	636.7	653.0
2039	429.4	705.1	673.3	670.8	640.7	655.6
2040	430.8	707.3	675.5	672.9	642.7	658.2
2041	431.6	708.8	676.9	674.3	644.0	660.8
2042	431.6	708.8	676.9	674.3	644.1	663.4
2043	434.1	712.9	680.8	678.2	647.8	666.0
2044	433.0	711.0	679.0	676.5	646.1	668.6
2045	433.8	712.3	680.3	677.7	647.3	671.2
2046	435.1	714.5	682.4	679.8	649.3	673.8
2047	436.8	717.2	685.0	682.4	651.8	676.4
2048	436.9	717.4	685.1	682.5	651.9	679.0
2049	439.1	721.0	688.6	686.0	655.2	681.6
2050	440.6	726.4	690.9	688.3	657.4	684.2

A list of input parameters related to the abatement techniques is given in Table C.9. As WHRS will be not considered at all, those input values are left blank and are not listed below.

Table C.9: Case study 1, input abatement technique data

Parameter	***Value***	***Unit***
EGR, first year of operation	*2021*	-
EGR, lifespan	*30*	years
EGR, total weight	*0.0*	T
EGR, purchase costs	*42.2*	$/kW
EGR, engineering costs for n.b.	*7.4*	$/kW
EGR, engineering costs for r.f.	-	$/kW
EGR, offhire time for r.f.	-	days
EGR, maintenance costs	*0.1*	$/MWh
EGR, consumables	*1.5*	$/MWh
EGR, slurry disposal	*0.1*	kg/MWh
EGR, add. engineers required	*0*	persons
EGR, wages engineers	*0*	$/month
EGR, SOx reduction potential	*38*	%
EGR, NOx reduction potential	*80*	%
EGR, CO2 reduction potential	*-7*	%
EGR, PM reduction potential	*34*	%
Scrubber, first year of operation	*2021*	-
Scrubber, lifespan	*15*	years
Scrubber, total weight	*10.5*	T
Scrubber, purchase costs	*130.8*	$/kW
Scrubber, engineering costs for n.b.	*43.7*	$/kW
Scrubber, engineering costs for r.f.	-	$/kW
Scrubber, offhire time for r.f.	-	days

Parameter	***Value***	***Unit***
Scrubber, maintenance costs	*0.3*	$/MWh
Scrubber, consumables	*0.4*	$/MWh
Scrubber, slurry disposal	*0.4*	kg/MWh
Scrubber, add. engineers required	*1*	persons
Scrubber, wages engineers	*3370*	$/month
Scrubber, SOx reduction potential	*97*	%
Scrubber, NOx reduction potential	*0*	%
Scrubber, CO2 reduction potential	*-1*	%
Scrubber, PM reduction potential	*94*	%
SCR, first year of operation	*2021*	-
SCR, lifespan	*30*	years
SCR, total weight	*5.2*	T
SCR, purchase costs	*43.6*	$/kW
SCR, engineering costs for n.b.	*10.9*	$/kW
SCR, engineering costs for r.f.	-	$/kW
SCR, offhire time for r.f.	-	days
SCR, maintenance costs	*0.7*	$/MWh
SCR, consumables	*2.7*	$/MWh
SCR, slurry disposal	*0.0*	kg/MWh
SCR, add. engineers required	*0*	persons
SCR, wages engineers	*0*	$/month
SCR, SOx reduction potential	*0*	%
SCR, NOx reduction potential	*95*	%
SCR, CO2 reduction potential	*-1*	%
SCR, PM reduction potential	*0*	%

D

Case study 1: results

This appendix gives a declaration of the results of the first case study, which is related to the graphs as shown in Chapter 7.3. Multiple calculations are done to obtain the fuel expenses. Therefore, intermediate results are given. For other calculations, only the final results are given. The ship speed for every leg is given in Table D.1 for the first operational year, including speed optimization. For the other operational years, the fuel price changes, which might result in a slightly different speed distribution.

Table D.1: Case study 1, speed non-SECA / speed SECA (knots)

Leg	***Port - Port***	***#0***	***#1, #4***	***#2, #3, #5, #6***	***#7, #8***
1	IJmuiden - Lagos	13.1 / 12.1	13.0 / 12.9	13.0 / 12.9	13.1 / 12.9
2	Lagos - Abidjan	13.0 / -	13.0 / -	13.0 / -	13.0 / -
3	Abidjan - Puebla del Caraminal	13.0 / -	13.0 / -	13.0 / -	13.0 / -
4	Puebla del Caraminal - IJmuiden	13.6 / 12.4	13.1 / 12.9	13.0 / 13.0	13.0 / 13.0

In Table D.2, the engine load per voyage outside SECAs is given for each compliance option for the first operational year. The engine load may only differ for the other years if the speed optimization changes or after the lifetime of the abatement technique has expired.

Table D.2: Case study 1, engine power per leg, non-SECA (kW)

Leg	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
1	2215	2164	2316	2186	2186	2339	2208	2215	2215
2	2144	2144	2294	2165	2165	2317	2187	2144	2144
3	2163	2163	2315	2185	2185	2338	2207	2163	2163
4	2478	2215	2316	2186	2237	2339	2208	2164	2164

In Table D.3, the engine load per voyage outside SECAs is given for each compliance option for the first operational year. The engine load may only differ for the other years if the speed optimization changes or after the lifetime of the abatement technique has expired.

Table D.3: Case study 1, engine power per leg, SECA (kW)

Leg	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
1	1755	2134	2283	2155	2155	2306	2177	2094	2094
2	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-
4	1887	2125	2332	2201	2146	2355	2223	2179	2179

In Table D.4, the specific fuel consumption of the main engine is given per leg for the first operational year. The rounded specific fuel consumptions do not differ between global areas and SECAs for the compliance methods. However, for the benchmark (#0), the specific fuel consumption does differ between the areas and is 183 g/kWh outside SECAs and 173 g/kWh inside SECAs.

Table D.4: Case study 1, SFC main engine per leg (g/kWh)

Leg	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
1	183/173	172	172	183	172	172	183	145	163
2	183	172	172	183	172	172	183	145	164
3	183	172	172	183	172	172	183	145	163
4	183/173	172	172	183	172	172	183	145	163

In Table D.5, the fuel consumption of the main engine outside SECAs is given per leg for the first operational year.

Table D.5: Case study 1, fuel consumption main engine, non-SECA (T)

Leg	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
1	116	107	115	116	109	124	117	92	104
2	14	13	14	14	14	15	15	11	13
3	88	82	88	89	83	95	90	70	78
4	16	14	15	15	14	16	15	12	13

In Table D.6, the fuel consumption of the main engine inside SECAs is given per leg for the first operational year.

Table D.6: Case study 1, fuel consumption main engine, SECA (T)

Leg	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
1	11	12	13	13	12	14	13	10	11
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	11	12	13	14	12	14	14	11	12

At sea, only one auxiliary engine is running. In port, two auxiliary engines are in operation. The engine loads are specified as input and are 518 kW at sea and 645 kW in port. The latter engine load is distributed over 2 engines. In the calculations, the power correction factor will be applied to obtain the fuel consumption figures. The specific fuel consumption depends on the engine type, fuel and abatement techniques. For every compliance option, the specific fuel consumptions of the auxiliary engines are given in Table D.7. The rounded specific fuel consumptions do not differ between global areas and SECAs. However, for the benchmark (#0), the specific fuel consumption does differ between the areas and is at sea 197 g/kWh outside SECAs and 184 g/kWh inside SECAs. In port, the specific fuel consumption is 198 g/kWh outside SECAs and 185 g/kWh inside SECAs.

Table D.7: Case study 1, SFC auxiliary engines (g/kWh)

Operation	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
Sea	197/184	184	185	197	184	198	197	160	160
Port	198/185	185	185	198	185	197	198	157	166

In Table D.8, the fuel consumption of the auxiliary engines outside SECAs is given per leg for the first operational year.

Table D.8: Case study 1, fuel consumption auxiliary engines, non-SECA (T)

Leg	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
1	29	28	30	30	28	32	30	24	24
2	4	3	4	4	4	4	4	3	3
3	23	21	23	23	21	25	23	18	18
4	4	4	4	4	4	4	4	3	3

In Table D.9, the fuel consumption of the auxiliary engines inside SECAs is given per leg for the first operational year.

Table D.9: Case study 1, fuel consumption auxiliary engines, SECA (T)

Leg	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
1	3	3	3	3	3	4	3	3	3
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	3	3	3	3	3	4	3	3	3

In Table D.10, the fuel consumption of the auxiliary engines in port is given for the first operational year. The amount of time that is spent in ports outside and inside SECAs is equal to the ratio of sailing time outside and inside SECAs.

Table D.10: Case study 1, fuel consumption auxiliary engines, port (T)

Operation	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
Port, non-SECA	165	156	166	168	157	179	170	132	140
Port, SECA	19	18	19	19	18	20	19	15	16

In Table D.11, the total fuel consumption per voyage is given for the first operational year. The consumption of the auxiliary engines in port is included.

Table D.11: Case study 1, fuel consumption per voyage (T)

Operation	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
ME non-SECA	235	217	232	234	219	250	236	185	208
ME SECA	22	24	26	26	25	28	27	21	23
AE non-SECA	225	212	226	228	214	244	230	181	188
AE SECA	25	24	26	26	24	28	26	21	22

In Table D.12, the yearly fuel consumption is given for the first operational year.

Table D.12: Case study 1, yearly fuel consumption (T)

Operation	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
Fuel non-SECA	HSFO	VLSGO	VLSGO	HSFO	VLSGO	HSFO	HSFO	LNG	LNG
Non-SECA consumption	1914	1787	1910	1926	1804	2059	1945	1522	1652
Fuel SECA	ULSGO	ULSGO	VLSGO	HSFO	ULSGO	HSFO	HSFO	LNG	LNG
SECA consumption	198	202	216	218	204	233	220	172	187

In Table D.13, the cumulative NPC are given for each year. The data is corresponding to Figure 7.4. The applied discount rate is 5%.

Table D.13: Case study 1, total NPC (M$)

Year	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
2020	0.4	0.4	0.5	0.6	0.5	0.7	0.7	2.4	2.4
2021	1.4	1.7	1.9	1.8	1.8	1.9	1.9	5.2	5.2
2022	2.4	3.0	3.3	2.9	3.1	3.1	3.1	7.8	7.9
2023	3.3	4.2	4.6	4.0	4.4	4.3	4.2	10.2	10.4
2024	4.2	5.3	5.8	5.0	5.6	5.4	5.2	12.5	12.8
2025	5.0	6.4	7.0	5.9	6.7	6.4	6.2	14.7	15.0
2026	5.8	7.4	8.2	6.8	7.8	7.4	7.2	16.8	17.1
2027	6.6	8.5	9.3	7.7	8.8	8.3	8.1	18.8	19.1
2028	7.3	9.4	10.4	8.5	9.9	9.3	9.0	20.6	21.1
2029	8.1	10.4	11.4	9.3	10.8	10.1	9.8	22.4	22.9
2030	8.8	11.4	12.5	10.3	11.9	11.1	10.8	24.8	25.3
2031	9.4	12.2	13.3	10.9	12.7	11.8	11.4	25.8	26.4
2032	10.0	12.9	14.1	11.4	13.4	12.4	12.0	26.8	27.4
2033	10.5	13.6	14.9	12.0	14.1	13.0	12.5	27.8	28.4
2034	11.0	14.3	15.7	12.5	14.8	13.5	13.0	28.7	29.4
2035	11.4	14.9	16.3	13.0	15.5	14.0	13.5	29.5	30.2
2036	11.9	15.5	17.0	13.6	16.1	14.7	14.2	30.3	31.1
2037	12.3	16.1	17.6	14.2	16.7	15.4	14.8	31.1	31.9
2038	12.7	16.7	18.3	14.8	17.3	16.0	15.3	31.8	32.7
2039	13.1	17.2	18.9	15.3	17.8	16.6	15.9	32.6	33.4
2040	13.5	17.7	19.4	15.8	18.3	17.1	16.4	33.2	34.1
2041	13.8	18.2	19.9	16.3	18.8	17.6	16.9	33.9	34.8
2042	14.2	18.7	20.5	16.8	19.3	18.1	17.4	34.5	35.5
2043	14.5	19.2	20.9	17.2	19.8	18.6	17.9	35.1	36.1
2044	14.8	19.6	21.4	17.6	20.2	19.1	18.3	35.6	36.7
2045	15.1	20.0	21.8	18.0	20.6	19.5	18.7	36.2	37.2
2046	15.4	20.4	22.3	18.4	21.0	19.9	19.1	36.7	37.7
2047	15.6	20.7	22.7	18.8	21.4	20.3	19.5	37.2	38.3
2048	15.9	21.1	23.1	19.2	21.8	20.7	19.8	37.6	38.8
2049	16.1	21.4	23.4	19.5	22.1	21.1	20.2	38.1	39.2
2050	16.4	21.8	23.8	19.8	22.5	21.4	20.5	38.5	39.7

In Figure D.14, a breakdown of the total life-cycle costs is given. In these figures, the discount rate is set to 0% to get insight in the real costs.

Table D.14: Case study 1, breakdown of life-cycle costs (M$)

	#0	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
CAPEX	2.67	2.67	3.02	3.92	3.06	4.28	4.31	15.00	14.93
OPEX	1.14	1.14	1.67	2.41	1.52	2.98	2.80	5.11	4.86
VE	27.38	38.20	40.62	32.60	38.64	34.73	32.98	47.48	50.18

In Figure D.15, a breakdown of the CAPEX is given. In these figures, the discount rate is set to 0% to get insight in the real costs.

Table D.15: Case study 1, breakdown of capital expenses (M$)

	#0	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
CAPEX engines	2.16	2.16	2.16	2.16	2.16	2.16	2.16	12.16	12.11
CAPEX abatement tech.	0	0	0.29	1.02	0.32	1.31	1.33	0	0
CAPEX financing	0.50	0.50	0.57	0.74	0.58	0.81	0.82	2.84	2.82

In Figure D.16, a breakdown of the OPEX is given. In these figures, the discount rate is set to 0% to get insight in the real costs.

Table D.16: Case study 1, breakdown of operational expenses (M$)

	#0	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**
OPEX engines	1.07	1.07	1.10	1.07	1.07	1.11	1.08	5.06	4.81
OPEX fuels	0.07	0.08	0.08	0.07	0.08	0.08	0.07	0.05	0.06
OPEX abatement tech.	0	0	0.49	1.27	0.38	1.80	1.65	0	0

In Figure D.17, a breakdown of the voyage expenses is given. In these figures, the discount rate is set to 0% to get insight in the real costs.

Table D.17: Case study 1, breakdown of voyage expenses (M$)

	#0	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**
VE fuel	27.38	38.20	40.62	32.53	38.57	34.66	32.85	31.79	34.49
VE loss of revenue	0	0	0	0.07	0.07	0.07	0.14	15.69	15.69

E

Case study 1: sensitivity data

In this appendix, the data used in the sensitivity analysis of the first case study is given. Table E.1 shows the data of the sensitivity analysis on the discount rate, corresponding to Figure 7.9.

Table E.1: Case study 1, sensitivity analysis on the discount rate (M$)

Discount rate	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
0%	31.18	42.01	45.31	38.92	43.22	41.97	40.08	67.59	69.98
2%	23.50	31.49	34.00	28.94	32.46	31.23	29.87	52.65	54.41
4%	18.33	24.43	26.40	22.30	25.23	24.09	23.06	42.43	43.75
6%	14.74	19.55	21.14	17.76	20.22	19.19	18.40	35.20	36.24
8%	12.18	16.08	17.40	14.56	16.66	15.74	15.12	29.95	30.78
10%	10.31	13.54	14.66	12.24	14.05	13.25	12.73	26.01	26.69

Table E.2 shows the data of the sensitivity analysis on the interest rate, corresponding to Figure 7.10.

Table E.2: Case study 1, sensitivity analysis on the interest rate (M$)

Interest rate	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
0%	16.07	21.46	23.19	19.37	22.15	20.92	20.02	36.77	37.95
2%	16.21	21.60	23.34	19.57	22.31	21.14	20.24	37.55	38.72
4%	16.34	21.74	23.50	19.77	22.47	21.36	20.47	38.32	39.49
6%	16.48	21.88	23.66	19.98	22.63	21.58	20.69	39.10	40.26
8%	16.62	22.02	23.81	20.18	22.78	21.80	20.91	39.87	41.04

Table E.3 shows the data of the sensitivity analysis on the scrubber price, corresponding to the payback times shown in Table 7.24.

Table E.3: Case study 1, sensitivity analysis on the scrubber price (M$)

Scrubber price	***#3, discount rate 0%***	***#3, discount rate 5%***
-40%	37.71	19.41
-20%	37.95	19.63
0%	38.18	19.85
+20%	38.42	20.07
+40%	38.65	20.29

Table E.4 shows the data of the sensitivity analysis on the price of low sulphur oils, corresponding to Figure 7.11.

Table E.4: Case study 1, sensitivity analysis on the low sulphur oil price (M$)

LS price	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
-20%	15.98	17.96	19.49	18.48	18.66	19.99	19.17	37.71	39.67
-10%	16.18	19.87	21.51	19.15	20.58	20.70	19.84	38.50	39.67
0%	16.38	21.77	23.54	19.82	22.50	21.41	20.52	38.50	39.67
+10%	16.58	23.68	25.56	20.49	24.43	22.12	21.19	38.50	39.67
+20%	16.78	25.58	27.59	21.16	26.35	22.83	21.87	38.50	39.67

Table E.5 shows the data of the sensitivity analysis on the LNG price, corresponding to Figure 7.12.

Table E.5: Case study 1, sensitivity analysis on the LNG price (M$)

LNG price	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
-20%	16.38	21.77	23.54	19.82	22.50	21.41	20.52	35.34	36.24
-10%	16.38	21.77	23.54	19.82	22.50	21.41	20.52	36.92	37.96
0%	16.38	21.77	23.54	19.82	22.50	21.41	20.52	38.50	39.67
+10%	16.38	21.77	23.54	19.82	22.50	21.41	20.52	40.08	41.38
+20%	16.38	21.77	23.54	19.82	22.50	21.41	20.52	41.42	43.10

Table E.6 shows the data of the sensitivity analysis on the specific gas tank costs, corresponding to Figure 7.13.

Table E.6: Case study 1, sensitivity analysis on the specific gas tank costs (M$)

Gas tank costs	***#2***	***#7***	***#8***
4000 $\$/\mathrm{m}^3$	23.54	33.66	34.82
5500 $\$/\mathrm{m}^3$	23.54	35.93	37.09
7000 $\$/\mathrm{m}^3$	23.54	38.19	39.36
8500 $\$/\mathrm{m}^3$	23.54	40.46	41.63

Table E.7 shows the data of the sensitivity analysis on the loss of revenue, corresponding to Figure 7.14.

Table E.7: Case study 1, sensitivity analysis on the loss of revenue (M$)

Loss of revenue	***#2***	***#7***	***#8***
0.0% loss	23.54	30.46	31.63
7.5% loss	23.54	34.63	35.80
15.0% loss	23.54	38.80	39.97

Table E.8 shows the data of the sensitivity analysis on the combined parameter variation of the low sulphur oil price and the LNG price, corresponding to Figure 7.15.

Table E.8: Case study 1, results of the proportional relationship between the low sulphur oil price and the LNG price (M$)

LS price	***LNG price***	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
-20%	-20%	15.98	17.96	19.49	18.48	18.66	19.99	19.17	35.34	36.24
-10%	-10%	16.18	19.87	21.51	19.15	20.58	20.70	19.84	36.92	37.96
0%	0%	16.38	21.77	23.54	19.82	22.50	21.41	20.52	38.50	39.67
+10%	+10%	16.58	23.68	25.56	20.49	24.43	22.12	21.19	40.08	41.38
+20%	+20%	16.78	25.58	27.59	21.16	26.35	22.83	21.87	41.66	43.10

Table E.9 shows the data of the sensitivity analysis on the combined parameter variation of the low sulphur oil price and the LNG price, corresponding to Figure 7.16.

Table E.9: Case study 1, results of the inverse proportional relationship between the low sulphur oil price and the LNG price (M$)

LS price	***LNG price***	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
-20%	+20%	15.98	17.96	19.49	18.48	18.66	19.99	19.17	37.67	43.10
-10%	+10%	16.18	19.87	21.51	19.15	20.58	20.70	19.84	39.52	41.38
0%	0%	16.38	21.77	23.54	19.82	22.50	21.41	20.52	38.80	39.97
+10%	-10%	16.58	23.68	25.56	20.49	24.43	22.12	21.19	36.92	37.96
+20%	-20%	16.78	25.58	27.59	21.16	26.35	22.83	21.87	35.34	36.24

F

Case study 2: input

This appendix gives the declaration of the input data for the second case study, which is subdivided in the categories that are used in the tool. A list of input parameters related to general project information and which options to consider is given in Table F.1.

Table F.1: Case study 2, input general project data

Parameter	***Value***	***Unit***
Project name	*Colour class*	-
First operational year	*2021*	-
Diesel Engine	*YES*	-
Dual Fuel Engine	*YES*	-
Gas Engine	*YES*	-
Fuel Cells	*NO*	-
HSFO	*YES*	-
ULSGO	*YES*	-
ULSFO	*YES*	-
VLSGO	*YES*	-
VLSFO	*YES*	-
LNG	*YES*	-
Bio-diesel	*NO*	-
Bio-LNG	*NO*	-
Hydrogen	*NO*	-
EGR	*YES*	-
Scrubber	*YES*	-
SCR	*YES*	-
WHRS	*NO*	-

A list of input parameters related to financing is given in Table F.2. As no retrofit is considered at all, those input values are left blank and are not listed below.

Table F.2: Case study 2, input financing data

Parameter	***Value***	***Unit***
Discount rate	*5*	%
Senior debt, repayment	*Yearly*	-
Senior debt, share	*70*	%
Senior debt, interest rate	*4.5*	%
Senior debt, tenor	*10*	years
Mezzanine debt, repayment	*No*	-
Mezzanine debt, share	*0*	%

Parameter	***Value***	***Unit***
Mezzanine debt, interest rate	*0*	%
Mezzanine debt, tenor	*0*	years
Seller’s credit, repayment	*Balloon*	-
Seller’s credit, share	*10*	%
Seller’s credit, interest rate	6	%
Seller’s credit, tenor	*10*	years

A list of input parameters related to ship specific data is given in Table F.3.

Table F.3: Case study 2, input ship data

Parameter	***Value***	***Unit***
Ship type	*Containership*	-
Propeller type	*Fixed Pitch Propeller*	-
Dayrate	*12,250*	$
Cargo capacity	*2256*	TEU
Ship speed at MCR	*19.6*	knots
Minimum service speed	*8.5*	knots
Remaining commercial lifetime	*25*	years
Main engine power	*13,100*	kW
Auxiliary engine power	*1650*	kW
Number of auxiliary engines	*4*	-
Drydock rate	*6000*	$/day
Original drydock period	*21*	days
First drydock year	*2025*	-
Crew responsible for safety duties	9	persons
Wages of crew responsible for safety duties	*2300*	$/month
Crew responsible for fuel handling	*4*	persons
Wages of crew responsible for fuel handling	*5785*	$/month
Insurance rate	*1.3*	%
EEDI reference parameter a	*174.22*	-
EEDI reference parameter b	*25175*	DWT
EEDI reference parameter c	*0.201*	-

A list of input parameters related to voyage data is given in Table F.4. The voyage schedule is separately given in Table F.5.

Table F.4: Case study 2, input voyage data

Parameter	***Value***	***Unit***
Required tank volume	*3343*	m^3
Simultaneous operations	*No*	-
Bunker time for low-flashpoint fuels	6	hours
Compensation stretch 1	*Radicatel - Papeete*	-
Compensation stretch 2	*Tauranga - Pisco*	-
Auxiliary power required in port	*1370*	kW
Auxiliary power required at sea	*1440*	kW
Sludge disposal costs	30	$/T
Carbon tax	*0*	$/T
Average container weight	*15*	T

Table F.5: Case study 2, input voyage schedule

#	*Port*	*Arrival date*	*Arrival time*	*Departure date*	*Departure time*
1	Rotterdam (Netherlands)	01-Jan	08:00	01-Jan	21:00
2	Dunkirk (France)	02-Jan	03:00	02-Jan	20:00
3	Radicatel (France)	03-Jan	12:00	04-Jan	07:00
4	Papeete (French Polynesia)	28-Jan	12:00	29-Jan	04:00
5	Noumea (New Caledonia)	05-Feb	23:00	06-Feb	18:30
6	Nelson (New Zealand)	10-Feb	20:00	11-Feb	12:00
7	Napier (New Zealand)	12-Feb	18:00	13-Feb	12:30
8	Tauranga (New Zealand)	14-Feb	13:00	15-Feb	09:30
9	Pisco (Peru)	01-Mar	20:00	02-Mar	15:00
10	Paita (Peru)	04-Mar	04:00	04-Mar	23:00
11	Philadelphia (USA)	13-Mar	17:00	15-Mar	08:00
12	Zeebrugge (Belgium)	23-Mar	12:00	24-Mar	04:00
13	Tilbury (UK)	24-Mar	13:00	25-Mar	06:00
14	Rotterdam (Netherlands)	25-Mar	21:00	26-Mar	08:00

A list of input parameters related to the engines is given in Table F.6. As fuel cells will be not considered at all, those input values are left blank and are not listed below.

Table F.6: Case study 2, input engine data

Parameter	*Value*	*Unit*
DE, engine costs	*251.0*	\$/kW
DE, gas tank costs	*0.0*	\$/m^3
DE, engineering costs	*120.0*	\$/kW
DE, maintenance costs	*1.5*	\$/MWh
DE, add. volume required	*0*	TEU
DE, ME rated speed	*127.0*	rpm
DE, ME SFC at MCR	*175.0*	g/kWh
DE, reference LHV	*42.7*	MJ/kg
DE, AE rated speed	*720*	rpm
DE, AE SFC at MCR	*187.0*	g/kWh
DF, engine costs	*396.7*	\$/kW
DF, gas tank costs	*7205.1*	\$/m^3
DF, engineering costs	*120.0*	\$/kW
DF, maintenance costs	*1.7*	\$/MWh
DF, add. volume required	*93*	TEU
DF, ME rated speed	*127.0*	rpm
DF, ME SFC at MCR	*174.0*	g/kWh
DF, reference LHV	*42.7*	MJ/kg
DF, AE rated speed	*720*	rpm
DF, AE SFC at MCR	*186.0*	g/kWh
GE, engine costs	*388.0*	\$/kW
GE, gas tank costs	*7205.1*	\$/m^3
GE, engineering costs	*120.0*	\$/kW
GE, maintenance costs	*1.0*	\$/MWh
GE, add. volume required	*93*	TEU
GE, ME rated speed	*1500*	rpm
GE, ME SFC at MCR	*181.4*	g/kWh
GE, reference LHV	*42.7*	MJ/kg
GE, AE rated speed	*1500*	rpm
GE, AE SFC at MCR	*181.4*	g/kWh

A list of input parameters related to the fuels is given in Table F.7. As bio-diesel, bio-LNG and hydrogen will be not considered at all, those input values are left blank and are not listed below. The fuel prices that are used are separately listed in Table F.8 and given in $/T.

Table F.7: Case study 2, input fuel data

Parameter	***Value***	***Unit***
HSFO, LHV	*40.0*	MJ/kg
HSFO, carbon content	*0.849*	%
HSFO, consumables	*0.61*	$/MWh
HSFO, sludge production	*1.5*	%
HSFO, SOx reduction potential	*0*	%
HSFO, NOx reduction potential	*0*	%
HSFO, CO2 reduction potential	*0*	%
HSFO, PM reduction potential	*0*	%
ULSGO, LHV	*42.7*	MJ/kg
ULSGO, carbon content	*0.874*	%
ULSGO, consumables	*1.12*	$/MWh
ULSGO, sludge production	*0.5*	%
ULSGO, SOx reduction potential	*97*	%
ULSGO, NOx reduction potential	*0*	%
ULSGO, CO2 reduction potential	*0*	%
ULSGO, PM reduction potential	*60*	%
ULSFO, LHV	*40.0*	MJ/kg
ULSFO, carbon content	*0.849*	%
ULSFO, consumables	*0.70*	$/MWh
ULSFO, sludge production	*1.0*	%
ULSFO, SOx reduction potential	*97*	%
ULSFO, NOx reduction potential	*0*	%
ULSFO, CO2 reduction potential	*0*	%
ULSFO, PM reduction potential	*0*	%
VLSGO, LHV	*42.7*	MJ/kg
VLSGO, carbon content	*0.847*	%
VLSGO, consumables	*1.12*	$/MWh
VLSGO, sludge production	*0.5*	%
VLSGO, SOx reduction potential	*86*	%
VLSGO, NOx reduction potential	*0*	%
VLSGO, CO2 reduction potential	*0*	%
VLSGO, PM reduction potential	*60*	%
VLSFO, LHV	*40.0*	MJ/kg
VLSFO, carbon content	*0.849*	%
VLSFO, consumables	*0.70*	$/MWh
VLSFO, sludge production	*1.1*	%
VLSFO, SOx reduction potential	*86*	%
VLSFO, NOx reduction potential	*0*	%
VLSFO, CO2 reduction potential	*0*	%
VLSFO, PM reduction potential	*0*	%
LNG, LHV	*49.2*	MJ/kg
LNG, carbon content	*0.750*	%
LNG, consumables	*1.06*	$/MWh
LNG, sludge production	*0.0*	%
LNG, SOx reduction potential	*100*	%
LNG, NOx reduction potential	*90*	%
LNG, CO2 reduction potential	*20*	%
LNG, PM reduction potential	*99*	%

Table F.8: Case study 2, fuel price projection ($/T)

Year	***HSFO***	***ULSGO***	***ULSFO***	***VLSGO***	***VLSFO***	***LNG (EU)***
2021	345.4	567.2	541.7	539.6	515.4	507.1
2022	354.9	582.8	556.6	554.5	529.6	524.1
2023	360.8	592.5	565.8	563.7	538.4	538.6
2024	366.6	602.0	574.9	572.7	547.0	559.2
2025	376.0	617.5	589.7	587.5	561.1	576.2
2026	383.2	629.3	601.0	598.7	571.9	589.6
2027	388.9	638.7	609.9	607.6	580.3	599.3
2028	393.3	645.8	616.7	614.4	586.8	609.1
2029	400.6	657.8	628.2	625.9	597.8	622.5
2030	408.1	670.0	639.9	637.5	608.9	632.2
2031	411.7	676.1	645.7	643.2	614.4	634.8
2032	416.1	683.3	652.6	650.1	620.9	637.4
2033	416.0	683.2	652.4	649.9	620.8	640.0
2034	418.9	687.8	656.9	654.4	625.0	642.6
2035	419.8	689.3	658.3	655.8	626.3	645.2
2036	424.4	696.9	655.5	663.0	633.3	647.8
2037	425.0	697.9	656.5	663.9	634.2	650.4
2038	426.7	700.7	669.1	666.6	636.7	653.0
2039	429.4	705.1	673.3	670.8	640.7	655.6
2040	430.8	707.3	675.5	672.9	642.7	658.2
2041	431.6	708.8	676.9	674.3	644.0	660.8
2042	431.6	708.8	676.9	674.3	644.1	663.4
2043	434.1	712.9	680.8	678.2	647.8	666.0
2044	433.0	711.0	679.0	676.5	646.1	668.6
2045	433.8	712.3	680.3	677.7	647.3	671.2

A list of input parameters related to the abatement techniques is given in Table F.9. As WHRS will be not considered at all, those input values are left blank and are not listed below.

Table F.9: Case study 2, input abatement technique data

Parameter	***Value***	***Unit***
EGR, first year of operation	*2021*	-
EGR, lifespan	*30*	years
EGR, total weight	*0.0*	T
EGR, purchase costs	*42.2*	$/kW
EGR, engineering costs for n.b.	*7.4*	$/kW
EGR, engineering costs for r.f.	-	$/kW
EGR, offhire time for r.f.	-	days
EGR, maintenance costs	*0.1*	$/MWh
EGR, consumables	*1.5*	$/MWh
EGR, slurry disposal	*0.1*	kg/MWh
EGR, add. engineers required	*0*	persons
EGR, wages engineers	*0*	$/month
EGR, SOx reduction potential	*38*	%
EGR, NOx reduction potential	*80*	%
EGR, CO2 reduction potential	*-7*	%
EGR, PM reduction potential	*34*	%
Scrubber, first year of operation	*2021*	-
Scrubber, lifespan	*15*	years
Scrubber, total weight	*35.5*	T
Scrubber, purchase costs	*130.8*	$/kW
Scrubber, engineering costs for n.b.	*43.7*	$/kW

Parameter	***Value***	***Unit***
Scrubber, engineering costs for r.f.	-	$/kW
Scrubber, offhire time for r.f.	-	days
Scrubber, maintenance costs	*0.3*	$/MWh
Scrubber, consumables	*0.4*	$/MWh
Scrubber, slurry disposal	*0.4*	kg/MWh
Scrubber, add. engineers required	*1*	persons
Scrubber, wages engineers	*3370*	$/month
Scrubber, SOx reduction potential	*97*	%
Scrubber, NOx reduction potential	*0*	%
Scrubber, CO2 reduction potential	*-1*	%
Scrubber, PM reduction potential	*94*	%
SCR, first year of operation	*2021*	-
SCR, lifespan	*30*	years
SCR, total weight	*17.7*	T
SCR, purchase costs	*43.6*	$/kW
SCR, engineering costs for n.b.	*10.9*	$/kW
SCR, engineering costs for r.f.	-	$/kW
SCR, offhire time for r.f.	-	days
SCR, maintenance costs	*0.7*	$/MWh
SCR, consumables	*2.7*	$/MWh
SCR, slurry disposal	*0.0*	kg/MWh
SCR, add. engineers required	*0*	persons
SCR, wages engineers	*0*	$/month
SCR, SOx reduction potential	*0*	%
SCR, NOx reduction potential	*95*	%
SCR, CO2 reduction potential	*-1*	%
SCR, PM reduction potential	*0*	%

G

Case study 2: results

This appendix gives a declaration of the results of the second case study, which is related to the graphs as shown in Chapter 8.2. Multiple calculations are done to obtain the fuel expenses, therefore intermediate results are given. For other calculations, only the final results are given. The ship speed for every leg is given in Table G.1 for the first operational year, including speed optimization. For the other operational years, the fuel price changes, which might result in a slightly different speed distribution.

Table G.1: Case study 2, speed non-SECA / speed SECA (knots)

Leg	*Port - Port*	*#0*	*#1, #4*	*#2, #3, #5, #6*	*#7, #8*
1	Rotterdam - Dunkirk	- / 17.5	- / 17.5	- / 17.5	- / 17.5
2	Dunkirk - Radicatel	- / 10.5	- / 10.5	- / 10.5	- / 10.5
3	Radicatel - Papeete	15.8 / 14.6	15.8 / 14.6	15.8 / 14.6	15.9 / 16.9
4	Papeete - Noumea	13.4 / -	13.4 / -	13.4 / -	13.4 / -
5	Noumea - Nelson	12.5 / -	12.5 / -	12.5 / -	12.5 / -
6	Nelson - Napier	10.6 / -	10.6 / -	10.6 / -	10.6 / -
7	Napier - Tauranga	11.6 / -	11.6 / -	11.6 / -	11.6 / -
8	Tauranga - Pisco	16.5 / -	16.5 / -	16.5 / -	16.8 / -
9	Pisco - Paita	17.0 / -	17.0 / -	17.0 / -	17.0 / -
10	Paita - Philadelphia	13.9 / 12.1	13.6 / 13.2	13.5 / 13.7	13.5 / 13.7
11	Philadelphia - Zeebrugge	18.4 / 16.8	17.6 / 17.5	17.5 / 17.6	17.5 / 17.6
12	Zeebrugge - Tilbury	- / 13.3	- / 13.3	- / 13.3	- / 13.3
13	Tilbury - Rotterdam	- / 10.7	- / 10.7	- / 10.7	- / 10.7

In Table G.2, the engine load per voyage outside SECAs is given for each compliance option for the first operational year. The engine load may only differ for the other years if the speed optimization changes or after the lifetime of the abatement technique has expired.

Table G.2: Case study 2, engine power per leg, non-SECA (kW)

Leg	*#0*	*#1*	*#2*	*#3*	*#4*	*#5*	*#6*	*#7*	*#8*
1	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-
3	6862	6862	7343	6931	6931	7416	7000	6993	6993
4	4207	4207	4502	4249	4249	4547	4292	4207	4207
5	3417	3417	3656	3451	3451	3693	3486	3417	3417
6	2092	2092	2238	2113	2113	2261	2134	2092	2092
7	2710	2710	2900	2737	2737	2929	2764	2710	2710
8	7884	7884	8436	7963	7963	8521	8043	8309	8309
9	8548	8548	9146	8633	8633	9238	8720	8548	8548
10	4672	4376	4580	4323	4420	4626	4367	4281	4281
11	10838	9485	9977	9418	9580	10251	9512	9324	9324
12	-	-	-	-	-	-	-	-	-
13	-	-	-	-	-	-	-	-	-

In Table G.3, the engine load per voyage outside SECAs is given for each compliance option for the first operational year. The engine load may only differ for the other years if the speed optimization changes or after the lifetime of the abatement technique has expired.

Table G.3: Case study 2, engine power per leg, SECA (kW)

Leg	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
1	9324	9324	9977	9418	9418	10077	9512	9324	9324
2	2014	2014	2155	2034	2034	2177	2055	2014	2014
3	5380	5380	5757	5434	5434	5814	5488	8422	8422
4	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-	-
10	3079	4020	4742	4476	4061	4789	4520	4431	4431
11	8251	9316	10132	9564	9409	10067	9659	9469	9469
12	4124	4124	4413	4165	4165	4457	4207	4124	4124
13	2151	2151	2302	2173	2173	2325	2195	2151	2151

In Table G.4, the specific fuel consumption of the main engine is given per leg for the first operational year outside SECAs.

Table G.4: Case study 2, SFC main engine per leg, non-SECA (g/kWh)

Leg	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	185	173	173	185	173	184	185	146	166
4	191	179	178	191	179	190	191	151	172
5	194	182	181	194	181	193	194	154	173
6	199	187	186	199	187	199	199	159	176
7	197	184	183	197	184	196	196	157	175
8	184	172	172	184	172	183	184	145	164
9	183	172	172	183	172	183	183	145	163
10	190	179	178	191	178	190	191	152	171
11	184	172	172	183	172	183	183	145	162
12	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0

In Table G.5, the specific fuel consumption of the main engine is given per leg for the first operational year inside SECAs.

Table G.5: Case study 2, SFC main engine per leg, SECA (g/kWh)

Leg	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
1	172	172	172	183	172	183	183	145	162
2	187	187	186	200	187	199	199	159	176
3	176	176	175	188	176	187	188	145	164
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0
10	183	180	178	190	180	189	190	151	171
11	172	172	172	183	172	183	183	145	162
12	179	179	178	191	179	190	191	152	172
13	186	186	186	199	186	198	199	159	176

In Table G.6, the fuel consumption of the main engine outside SECAs is given per leg for the first operational year.

Table G.6: Case study 2, fuel consumption main engine, non-SECA (T)

Leg	*#0*	*#1*	*#2*	*#3*	*#4*	*#5*	*#6*	*#7*	*#8*
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	715	670	714	722	676	769	728	573	650
4	150	141	150	152	142	162	153	119	135
5	65	61	64	72	61	69	66	51	58
6	13	12	12	14	12	13	13	10	11
7	13	12	13	13	12	14	13	10	12
8	502	470	502	507	475	541	512	411	463
9	58	54	58	59	55	63	59	46	52
10	148	133	140	142	134	151	143	112	126
11	182	155	164	166	157	179	167	130	147
12	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0

In Table G.7, the fuel consumption of the main engine inside SECAs is given per leg for the first operational year.

Table G.7: Case study 2, fuel consumption main engine, SECA (T)

Leg	*#0*	*#1*	*#2*	*#3*	*#4*	*#5*	*#6*	*#7*	*#8*
1	10	10	10	10	10	11	10	8	9
2	6	6	6	6	6	7	7	5	6
3	17	17	18	18	17	19	18	19	21
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0
10	24	29	32	33	29	35	33	26	29
11	148	161	174	175	162	186	177	137	152
12	7	7	7	7	7	8	7	6	6
13	6	6	6	6	6	7	7	5	6

The auxiliary power demand is so low that both in port and at sea, only one auxiliary engine is in operation (on average). The engine loads are specified as input and are 1440 kW at sea and 1370 kW in port. In the calculation, the power correction factor will be applied to obtain the fuel consumption figures. The specific fuel consumption depends on the engine type, fuel and abatement techniques. For every compliance option, the specific fuel consumption of the auxiliary engines is given in Table G.9.

Table G.8: Case study 2, SFC auxiliary engines (g/kWh)

Operation	*#0*	*#1*	*#2*	*#3*	*#4*	*#5*	*#6*	*#7*	*#8*
Sea, global	197	185	186	198	185	199	198	161	159
Sea, SECA	185	185	186	198	185	199	198	161	159
Port, global	197	184	185	197	184	198	197	160	160
Port, SECA	184	184	185	197	184	198	197	160	160

In Table G.9, the fuel consumption of the auxiliary engines outside SECAs is given per leg for the first operational year.

Table G.9: Case study 2, fuel consumption auxiliary engines, non-SECA (T)

Leg	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***	
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	160	150	162	162	152	174	164	129	128
4	53	50	54	54	50	58	54	43	43
5	28	26	28	28	26	30	28	23	22
6	9	8	9	9	8	9	9	7	7
7	7	7	7	7	7	8	7	6	6
8	98	92	99	100	93	107	101	79	78
9	11	10	11	11	10	11	11	9	8
10	47	45	49	49	46	53	50	40	39
11	26	25	28	28	26	30	28	22	22
12	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0

In Table G.10, the fuel consumption of the auxiliary engines inside SECAs is given per leg for the first operational year.

Table G.10: Case study 2, fuel consumption auxiliary engines, SECA (T)

Leg	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***	
1	2	2	2	2	2	2	2	1	1
2	4	4	5	5	4	5	5	4	4
3	5	5	5	5	5	5	5	4	3
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0
10	12	11	11	11	11	12	11	9	9
11	28	27	29	29	27	31	29	24	23
12	2	2	3	3	2	3	3	2	2
13	4	4	4	4	4	5	4	3	3

In Table G.11, the fuel consumption of the auxiliary engines in port is given for the first operational year. The amount of time that is spent in ports outside and inside SECAs is equal to the ratio of sailing time outside and inside SECAs.

Table G.11: Case study 2, fuel consumption auxiliary engines, port (T)

Operation	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
Port, non-SECA	62	58	63	63	59	68	63	53	53
Port, SECA	8	8	8	8	8	9	8	7	7

In Table G.13, the total fuel consumption per voyage is given for the first operational year. The consumption of the auxiliary engines in port are included.

Table G.12: Case study 2, fuel consumption per voyage (T)

Operation	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
ME non-SECA	1845	1708	1819	1837	1724	1962	1855	1462	1653
ME SECA	218	234	254	256	237	272	259	206	229
AE non-SECA	501	471	508	509	476	548	515	410	407
AE SECA	64	62	66	66	63	72	67	53	53

In Table G.13, the yearly fuel consumption is given for the first operational year.

Table G.13: Case study 2, yearly fuel consumption (T)

Operation	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
Fuel non-SECA	HSFO	VLSGO	VLSGO	HSFO	VLSGO	HSFO	HSFO	LNG	LNG
Non-SECA consumption	10193	9470	10110	10194	9563	10908	2369	8136	8952
Fuel SECA	ULSGO	ULSGO	VLSGO	HSFO	ULSGO	HSFO	HSFO	LNG	LNG
SECA consumption	1226	1287	1392	1402	1300	1493	326	1124	1224

In Table G.14, the cumulative NPC are given for each year. The data is corresponding to Figure 7.4. The applied discount rate is 5%.

Table G.14: Case study 2, total NPC (M$)

Year	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
2020	1.5	1.5	1.7	2.1	1.7	2.3	2.4	6.9	6.8
2021	6.4	7.9	8.7	7.5	8.4	8.1	7.9	15.5	15.8
2022	11.2	14.2	15.5	12.6	14.9	13.7	13.2	23.8	24.5
2023	15.7	20.3	22.0	17.5	21.1	19.0	18.3	31.7	32.8
2024	20.2	26.1	28.3	22.2	27.1	24.2	23.2	39.3	40.7
2025	24.2	31.5	34.1	26.6	32.7	28.9	27.7	46.3	48.1
2026	28.3	36.9	40.0	31.0	38.3	33.6	32.3	53.2	55.4
2027	32.3	42.2	45.7	35.1	43.7	38.2	36.6	59.8	62.3
2028	36.1	47.2	51.1	39.1	48.9	42.5	40.7	66.1	68.9
2029	39.7	52.1	56.4	43.0	53.9	46.7	44.7	72.0	75.2
2030	43.5	57.0	61.7	47.1	59.0	51.2	49.0	79.6	83.1
2031	46.5	61.2	66.1	50.2	63.3	54.5	52.1	83.4	87.2
2032	49.5	65.2	70.5	53.1	67.3	57.7	55.1	87.1	91.2
2033	52.3	69.0	74.6	55.9	71.2	60.7	58.0	90.6	95.0
2034	54.9	72.7	78.5	58.6	75.0	63.6	60.7	94.0	98.6
2035	57.3	75.9	82.0	61.0	78.3	66.2	63.2	97.0	101.9
2036	59.8	79.3	85.6	64.3	81.7	69.8	66.6	100.1	105.2
2037	62.1	82.5	89.1	67.5	85.0	73.2	69.9	103.0	108.4
2038	64.3	85.6	92.4	70.6	88.1	76.5	73.0	105.8	111.4
2039	66.5	88.5	95.5	73.6	91.1	79.7	76.0	108.5	114.3
2040	68.4	91.2	98.4	76.2	93.8	82.5	78.7	110.9	116.9
2041	70.4	93.9	101.2	78.9	96.6	85.4	81.4	113.3	119.6
2042	72.2	96.4	104.0	81.4	99.2	88.1	84.0	115.7	122.1
2043	74.0	98.9	106.6	83.9	101.6	90.8	86.5	117.9	124.5
2044	75.7	101.2	109.1	86.2	104.0	93.2	88.8	120.0	126.8
2045	77.2	103.3	111.3	88.3	106.1	95.5	91.0	122.0	128.9

In Table G.15, a breakdown of the total life-cycle costs is given. In those data, the discount rate is set to 0% to get insight in the real costs.

Table G.15: Case study 2, breakdown of life-cycle costs (M$)

	#0	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
CAPEX	9.01	9.01	10.22	13.25	10.34	14.46	14.58	42.26	42.05
OPEX	4.18	4.21	6.39	8.01	5.72	10.39	9.56	13.23	12.13
VE	122.58	169.79	180.45	139.09	171.51	148.26	140.51	146.26	160.34

In Table G.16, a breakdown of the CAPEX is given. In those data, the discount rate is set to 0% to get insight in the real costs.

Table G.16: Case study 2, breakdown of capital expenses (M$)

	#0	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
CAPEX engines	7.31	7.31	7.31	7.31	7.31	7.31	7.31	34.27	34.09
CAPEX abatement tech.	0	0	0.98	3.44	1.07	4.41	4.51	0	0
CAPEX financing	1.70	1.70	1.93	2.51	1.96	2.73	2.76	7.99	7.95

In Table G.17, a breakdown of the OPEX is given. In those data, the discount rate is set to 0% to get insight in the real costs.

Table G.17: Case study 2, breakdown of operational expenses (M$)

	#0	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
OPEX engines	3.87	3.87	4.03	3.88	3.89	4.04	3.91	12.98	11.86
OPEX fuels	0.31	0.34	0.36	0.32	0.34	0.34	0.32	0.24	0.27
OPEX abatement tech.	0	0	2.00	3.81	1.49	6.01	5.33	0	0

In Table G.18, a breakdown of the voyage expenses is given. In those data, the discount rate is set to 0% to get insight in the real costs.

Table G.18: Case study 2, breakdown of voyage expenses (M$)

	#0	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
VE fuel	122.58	167.79	180.45	139.03	171.46	148.20	140.40	142.32	156.40
VE loss of revenue	0	0	0	0.06	0.05	0.06	0.11	3.94	3.94

H

Case study 2: sensitivity data

In this appendix, the data used in the sensitivity analysis of the second case study is given. Table H.1 shows the data of the sensitivity analysis on the scrubber price, corresponding to the payback times shown in Table 8.7.

Table H.1: Case study 2, sensitivity analysis on the scrubber price (M$)

Scrubber price	***#3, discount rate 0%***	***#3, discount rate 5%***
-40%	156.25	86.85
-20%	157.02	87.63
0%	157.80	88.38
+20%	158.58	89.13
+40%	159.36	89.88

Table H.2 shows the data of the sensitivity analysis on the price of low sulphur oils, corresponding to Figure 8.9.

Table H.2: Case study 2, sensitivity analysis on the low sulphur oil price (M$)

LS price	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
-20%	74.95	84.54	91.44	82.95	87.22	89.82	85.58	118.26	128.93
-10%	76.09	93.91	101.39	85.62	96.68	92.66	88.28	121.97	128.93
0%	77.21	103.27	111.35	88.29	106.14	95.49	90.98	121.97	128.93
+10%	78.33	112.64	121.30	90.96	115.59	98.33	93.67	121.97	128.93
+20%	79.43	122.00	131.25	93.63	125.05	101.17	96.37	121.97	128.93

Table H.3 shows the data of the sensitivity analysis on the LNG price, corresponding to Figure 8.10.

Table H.3: Case study 2, sensitivity analysis on the LNG price (M$)

LNG price	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***	
-20%	77.21	103.27	111.35	88.29	106.14	95.49	90.98	106.31	111.72
-10%	77.21	103.27	111.35	88.29	106.14	95.49	90.98	114.14	120.33
0%	77.21	103.27	111.35	88.29	106.14	95.49	90.98	121.97	128.93
+10%	77.21	103.27	111.35	88.29	106.14	95.49	90.98	129.80	137.54
+20%	77.21	103.27	111.35	88.29	106.14	95.49	90.98	136.60	146.14

Table H.4 shows the data of the sensitivity analysis on the specific gas tank costs, corresponding to Figure 8.11.

Table H.4: Case study 2, sensitivity analysis on the specific gas tank costs (M$)

Gas tank costs	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
4000 m^3	77.21	103.27	111.35	88.29	106.14	95.49	90.98	109.38	116.34
5500 m^3	77.21	103.27	111.35	88.29	106.14	95.49	90.98	115.28	122.23
7000 m^3	77.21	103.27	111.35	88.29	106.14	95.49	90.98	121.17	128.13
8500 m^3	77.21	103.27	111.35	88.29	106.14	95.49	90.98	127.06	134.02

Table H.5 shows the data of the sensitivity analysis on the voyage duration.

Table H.5: Case study 2, sensitivity analysis on the voyage duration (M$)

Voyage duration	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
11 weeks	94.29	126.97	137.10	107.07	130.22	116.01	110.09	147.54	154.36
12 weeks	77.21	103.27	111.35	88.29	106.14	95.49	90.98	121.97	128.93
13 weeks	60.82	80.76	87.28	70.56	83.33	76.44	73.00	100.57	105.44

Table H.6 shows the data of the sensitivity analysis on the combined parameter variation of the LNG price and the LNG tank costs, corresponding to Figure 8.12.

Table H.6: Case study 2, results of the proportional relationship between the LNG price and the LNG tank costs (M$)

LNG price	***LNG tank costs***	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
-20%	-20%	77.21	103.27	111.35	88.29	106.14	95.49	90.98	100.65	106.06
-10%	-10%	77.21	103.27	111.35	88.29	106.14	95.49	90.98	111.31	117.50
0%	0%	77.21	103.27	111.35	88.29	106.14	95.49	90.98	121.97	128.93
+10%	+10%	77.21	103.27	111.35	88.29	106.14	95.49	90.98	132.63	140.37
+20%	+20%	77.21	103.27	111.35	88.29	106.14	95.49	90.98	142.26	151.80

Table H.7 shows the data of the sensitivity analysis on the combined parameter variation of the LNG price and the LNG tank costs, corresponding to Figure 8.13.

Table H.7: Case study 2, results of the inverse proportional relationship between the LNG price and the LNG tank costs (M$)

LNG price	***LNG tank costs***	***#0***	***#1***	***#2***	***#3***	***#4***	***#5***	***#6***	***#7***	***#8***
-20%	+20%	77.21	103.27	111.35	88.29	106.14	95.49	90.98	111.97	117.38
-10%	+10%	77.21	103.27	111.35	88.29	106.14	95.49	90.98	116.97	123.16
0%	0%	77.21	103.27	111.35	88.29	106.14	95.49	90.98	121.97	128.93
+10%	-10%	77.21	103.27	111.35	88.29	106.14	95.49	90.98	126.97	134.71
+20%	-20%	77.21	103.27	111.35	88.29	106.14	95.49	90.98	130.94	140.48

I

Case study 3: input

This appendix gives the declaration of the input data for the third case study, which is subdivided in the categories that are used in the tool. A list of input parameters related to general project information and which options to consider is given in Table I.1.

Table I.1: Case study 3, input general project data

Parameter	***Value***	***Unit***
Project name	*Baltic Klipper*	-
First operational year	*2020*	-
Diesel Engine	*YES*	-
Dual Fuel Engine	*NO*	-
HSFO	*YES*	-
ULSGO	*YES*	-
ULSFO	*YES*	-
VLSGO	*YES*	-
VLSFO	*YES*	-
LNG	*NO*	-
Bio-diesel	*NO*	-
Bio-LNG	*NO*	-
EGR	*NO*	-
Scrubber	*YES*	-
SCR	*NO*	-
WHRS	*NO*	-

A list of input parameters related to financing the retrofit project is given in Table I.2.

Table I.2: Case study 3, input financing data

Parameter	***Value***	***Unit***
Discount rate	*5*	%
Senior debt, repayment	*Yearly*	-
Senior debt, share	*85*	%
Senior debt, interest rate	*3.4*	%
Senior debt, tenor	*8*	years
Mezzanine debt, repayment	*No*	-
Mezzanine debt, share	*0*	%
Mezzanine debt, interest rate	*0*	%
Mezzanine debt, tenor	*0*	years

Parameter	***Value***	***Unit***
Seller's credit, repayment	*No*	-
Seller's credit, share	*0*	%
Seller's credit, interest rate	*0*	%
Seller's credit, tenor	*0*	years

A list of input parameters related to ship specific data is given in Table I.3.

Table I.3: Case study 3, input ship data

Parameter	***Value***	***Unit***
Ship type	*Reefership*	-
Propeller type	*Fixed Pitch Propeller*	-
Dayrate	*17,000*	$
Cargo capacity	*661,636*	cbft
Deadweight	*15693*	DWT
Ship speed at MCR	*21.1*	knots
Minimum service speed	*12.0*	knots
Remaining commercial lifetime	*20*	years
Main engine power	*14280*	kW
Auxiliary engine power	*1620*	kW
Number of auxiliary engines	*4*	-
Drydock rate	*6000*	$/day
Original drydock period	*21*	days
First drydock year	*2020*	-
Crew responsible for safety duties	*9*	persons
Wages of crew responsible for safety duties	*2300*	$/month
Crew responsible for fuel handling	*4*	persons
Wages of crew responsible for fuel handling	*5785*	$/month
Insurance rate	*1.3*	%

A list of input parameters related to voyage data is given in Table I.4. The voyage schedule is separately given in Table I.5.

Table I.4: Case study 3, input voyage data

Parameter	***Value***	***Unit***
Required tank volume	*0*	m^3
Simultaneous operations	*No*	-
Bunker time for low-flashpoint fuels	*0*	hours
Compensation stretch 1	*None*	-
Compensation stretch 2	*None*	-
Auxiliary power required in port	*977*	kW
Auxiliary power required at sea	*1112*	kW
Sludge disposal costs	*30*	$/T
Carbon tax	*0*	$/T
Average container weight	*15*	T

Table I.5: Case study 3: input voyage schedule

#	*Port*	*Arrival date*	*Arrival time*	*Departure date*	*Departure time*
1	Turbo (Colombia)	01-Jan	08:00	01-Jan	19:30
2	Santa Marta (Colombia)	02-Jan	11:00	03-Jan	00:30
3	Manzanillo (Dom. Republic)	04-Jan	11:30	06-Jan	09:30
4	Dover (UK)	15-Jan	08:00	17-Jan	21:00
5	Flushing (Netherlands)	18-Jan	04:00	20-Jan	00:30
6	Le Havre (France)	20-Jan	12:30	21-Jan	03:00
7	Fort de France (Martinique)	29-Jan	17:00	30-Jan	02:00
8	Bridgetown (Barbados)	30-Jan	13:00	31-Jan	00:00
9	St. Georges (Grenada)	31-Jan	10:00	31-Jan	19:00
10	Castries (Saint Lucia)	01-Feb	02:00	01-Feb	14:30
11	Turbo (Colombia)	03-Feb	22:30	05-Feb	08:00

A list of input parameters related to the engines is given in Table I.6. As dual-fuel engines will be not considered at all, those input values are left blank and are not listed below.

Table I.6: Case study 3, input engine data

Parameter	*Value*	*Unit*
DE, engine costs	*251.0*	$/kW
DE, gas tank costs	*0.0*	$/m^3
DE, maintenance costs	*1.5*	$/MWh
DE, ME rated speed	*105.0*	rpm
DE, ME SFC at MCR	*173.0*	g/kWh
DE, reference LHV	*42.7*	MJ/kg
DE, AE rated speed	*720*	rpm
DE, AE SFC at MCR	*197.4*	g/kWh

A list of input parameters related to the fuels is given in Table I.7. As LNG and biofuels will be not considered at all, those input values are left blank and are not listed below. The fuel prices that are used are separately listed in Table I.8 and given in $/T.

Table I.7: Case study 3, input fuel data

Parameter	*Value*	*Unit*
HSFO, LHV	*40.0*	MJ/kg
HSFO, carbon content	*0.849*	%
HSFO, consumables	*0.61*	$/MWh
HSFO, sludge production	*1.5*	%
HSFO, SOx reduction potential	*0*	%
HSFO, NOx reduction potential	*0*	%
HSFO, CO2 reduction potential	*0*	%
HSFO, PM reduction potential	*0*	%
ULSGO, LHV	*42.7*	MJ/kg
ULSGO, carbon content	*0.874*	%
ULSGO, consumables	*1.12*	$/MWh
ULSGO, sludge production	*0.5*	%
ULSGO, SOx reduction potential	*97*	%
ULSGO, NOx reduction potential	*0*	%
ULSGO, CO2 reduction potential	*0*	%
ULSGO, PM reduction potential	*60*	%
ULSFO, LHV	*40.0*	MJ/kg
ULSFO, carbon content	*0.849*	%
ULSFO, consumables	*0.70*	$/MWh
ULSFO, sludge production	*1.0*	%

Parameter	***Value***	***Unit***
ULSFO, SOx reduction potential	*97*	%
ULSFO, NOx reduction potential	*0*	%
ULSFO, CO2 reduction potential	*0*	%
ULSFO, PM reduction potential	*0*	%
VLSGO, LHV	*42.7*	MJ/kg
VLSGO, carbon content	*0.847*	%
VLSGO, consumables	*1.12*	$/MWh
VLSGO, sludge production	*0.5*	%
VLSGO, SOx reduction potential	*86*	%
VLSGO, NOx reduction potential	*0*	%
VLSGO, CO2 reduction potential	*0*	%
VLSGO, PM reduction potential	*60*	%
VLSFO, LHV	*40.0*	MJ/kg
VLSFO, carbon content	*0.849*	%
VLSFO, consumables	*0.70*	$/MWh
VLSFO, sludge production	*1.1*	%
VLSFO, SOx reduction potential	*86*	%
VLSFO, NOx reduction potential	*0*	%
VLSFO, CO2 reduction potential	*0*	%
VLSFO, PM reduction potential	*0*	%

Table I.8: Case study 3, fuel price projection ($/T)

Year	***HSFO***	***ULSGO***	***ULSFO***	***VLSGO***	***VLSFO***
2020	336.0	551.7	526.9	577.4	501.3
2021	345.4	567.2	541.7	539.6	515.4
2022	354.9	582.8	556.6	554.5	529.6
2023	360.8	592.5	565.8	563.7	538.4
2024	366.6	602.0	574.9	572.7	547.0
2025	376.0	617.5	589.7	587.5	561.1
2026	383.2	629.3	601.0	598.7	571.9
2027	388.9	638.7	609.9	607.6	580.3
2028	393.3	645.8	616.7	614.4	586.8
2029	400.6	657.8	628.2	625.9	597.8
2030	408.1	670.0	639.9	637.5	608.9
2031	411.7	676.1	645.7	643.2	614.4
2032	416.1	683.3	652.6	650.1	620.9
2033	416.0	683.2	652.4	649.9	620.8
2034	418.9	687.8	656.9	654.4	625.0
2035	419.8	689.3	658.3	655.8	626.3
2036	424.4	696.9	655.5	663.0	633.3
2037	425.0	697.9	656.5	663.9	634.2
2038	426.7	700.7	669.1	666.6	636.7
2039	429.4	705.1	673.3	670.8	640.7

A list of input parameters related to the abatement techniques is given in Table I.9. As EGR, SCR and WHRS will be not considered at all, those input values are left blank and are not listed below.

Table I.9: Case study 3, input abatement technique data

Parameter	***Value***	***Unit***
Scrubber, first year of operation	*2021*	-
Scrubber, lifespan	*15*	years
Scrubber, total weight	*37.4*	T
Scrubber, purchase costs	*130.8*	\$/kW
Scrubber, engineering costs	*103.7*	\$/kW
Scrubber, offhire time	*20*	days
Scrubber, maintenance costs	*0.3*	\$/MWh
Scrubber, consumables	*0.4*	\$/MWh
Scrubber, sludge disposal	*0.4*	\$/MWh
Scrubber, add. engineer required	*0.4*	\$/MWh
Scrubber, Wages engineers	*0.4*	\$/MWh
Scrubber, SO_x reduction potential	*97*	%
Scrubber, NO_x reduction potential	*0*	%
Scrubber, CO_2 reduction potential	*-1*	%
Scrubber, PM reduction potential	*94*	%

J

Case study 3: results

This appendix gives the declaration of the results of the third case study, which are related to the graphs as shown in Chapter 9.3. Multiple calculations are done to obtain the fuel expenses, therefore intermediate results are given. For other calculations, only the final results are given. The ship speed for every leg is given in Table J.1 for the second operational year, including speed optimization. The results of the second operational year are given, because this is the first operation year of the scrubber. In the first operational year, both scenario's have equal results. For the other operational years, only the fuel price changes and might result in a slightly different speed distribution.

Table J.1: Case study 3, speed non-SECA / speed SECA (knots)

Leg	***Port - Port***	***#0***	***#1***	***#2***
1	Turbo - Santa Marta	18.3 / -	18.3 / -	18.3 / -
2	Santa Marta - Manzanillo	18.4 / -	18.4 / -	18.4 / -
3	Manzanillo - Dover	18.3 / 15.9	18.3 / 15.9	18.1 / 18.4
4	Dover - Flushing	- / 13.1	- / 13.1	- / 13.1
5	Flushing - Le Havre	- / 16.1	- / 16.1	- / 16.1
6	Le Havre - Fort de France	16.5 / 13.9	16.5 / 16.1	16.3 / 16.6
7	Fort de France - Bridgetown	12.2 / -	12.2 / -	12.2 / -
8	Bridgetown - St. Georges	16.2 / -	16.2 / -	16.2 / -
9	St. Georges - Castries	18.7 / -	18.7 / -	18.7 / -
10	Castries - Turbo	19.2 / -	19.2 / -	19.2 / -

In Table J.2, the engine load per voyage outside SECAs is given for each compliance option for the second operational year, because this is the first operational year of the scrubber. The engine load may only differ for the other years if the speed optimization changes or after the lifetime of the abatement technique has expired.

Table J.2: Case study 3, engine power per leg, non-SECA (kW)

Leg	***#0***	***#1***	***#2***
1	9252	9252	9345
2	9470	9470	9564
3	9316	9014	9104
4	-	-	-
5	-	-	-
6	6829	6583	6649
7	2748	2748	2748
8	6463	6463	6463
9	9963	9963	9963
10	10753	10753	10753

In Table J.3, the engine load per voyage outside SECAs is given for each compliance option for the second operational year, because this is the first operational year of the scrubber. The engine load may only differ for the other years if the speed optimization changes or after the lifetime of the abatement technique has expired.

Table J.3: Case study 3, engine power per leg, SECA (kW)

Leg	***#0***	***#1***	***#2***
1	-	-	-
2	-	-	-
3	6085	9397	9491
4	3451	3451	3486
5	6324	6324	6387
6	4419	6898	6967
7	-	-	-
8	-	-	-
9	-	-	-
10	-	-	-

In Table J.4, the specific fuel consumption of the main engine is given per leg for the second operational year outside SECAs, because this is the first operational year of the scrubber.

Table J.4: Case study 3, SFC main engine per leg, non-SECA (g/kWh)

Leg	***#0***	***#1***	***#2***
1	183	172	183
2	183	172	183
3	183	172	183
4	0	0	0
5	0	0	0
6	186	175	186
7	197	185	197
8	187	175	186
9	183	172	183
10	183	172	183

In Table G.5, the specific fuel consumption of the main engine is given per leg for the second operational year inside SECAs, because this is the first operational year of the scrubber.

Table J.5: Case study 3, SFC main engine per leg, SECA (g/kWh)

Leg	***#0***	***#1***	***#2***
1	0	0	0
2	0	0	0
3	172	172	183
4	183	183	195
5	175	175	187
6	174	174	186
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0

In Table J.6, the fuel consumption of the main engine outside SECAs is given per leg for the second operational year, because this is the first operational year of the scrubber.

Table J.6: Case study 3, fuel consumption main engine, non-SECA (T)

Leg	***#0***	***#1***	***#2***
1	26	25	27
2	61	57	61
3	339	310	335
4	0	0	0
5	0	0	0
6	243	222	240
7	6	6	6
8	12	11	12
9	13	12	13
10	110	103	111

In Table J.7, the fuel consumption of the main engine inside SECAs is given per leg for the second operational year, because this is the first operational year of the scrubber.

Table J.7: Case study 3, fuel consumption main engine, SECA (T)

Leg	***#0***	***#1***	***#2***
1	0	0	0
2	0	0	0
3	17	23	23
4	4	4	4
5	13	13	13
6	11	15	15
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0

The auxiliary power demand is so low that both in port and at sea, only one auxiliary engine is in operation (on average). The engine loads are specified as input and are 1112 kW at sea and 977 kW in port. In the calculation, the power correction factor will be applied to obtain the fuel consumption figures. The specific fuel consumption depends on the engine type, fuel and abatement techniques. For every compliance option, the specific fuel consumption of the auxiliary engines is given in Table J.9.

Table J.8: Case study 3, SFC auxiliary engines (g/kWh)

Operation	***#0***	***#1***	***#2***
Sea, global	196	184	196
Sea, SECA	184	184	196
Port, global	197	184	196
Port, SECA	184	184	196

In Table J.9, the fuel consumption of the auxiliary engines outside SECAs is given per leg for the second operational year, because this is the first operational year of the scrubber.

Table J.9: Case study 3, fuel consumption auxiliary engines, non-SECA (T)

Leg	***#0***	***#1***	***#2***
1	3	3	3
2	8	7	8
3	43	41	44
4	0	0	0
5	0	0	0
6	42	39	43
7	2	2	2
8	2	2	2
9	2	1	2
10	12	11	12

In Table J.10, the fuel consumption of the auxiliary engines inside SECAs is given per leg for the second operational year, because this is the first operational year of the scrubber.

Table J.10: Case study 3, fuel consumption auxiliary engines, SECA (T)

Leg	***#0***	***#1***	***#2***
1	0	0	0
2	0	0	0
3	3	3	3
4	1	1	2
5	2	2	3
6	3	3	3
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0

In Table J.11, the fuel consumption of the auxiliary engines in port is given for the second operational year. The amount of time that is spent in ports outside and inside SECAs is equal to the ratio of sailing time outside and inside SECAs.

Table J.11: Case study 3, fuel consumption auxiliary engines, port (T)

Operation	***#0***	***#1***	***#2***
Port, non-SECA	85	81	87
Port, SECA	8	7	7

In Table J.13, the total fuel consumption per voyage is given for the second operational year. The consumption of the auxiliary engines in port are included.

Table J.12: Case study 3, fuel consumption per voyage (T)

Operation	***#0***	***#1***	***#2***
ME non-SECA	809	747	805
ME SECA	46	55	60
AE non-SECA	200	189	203
AE SECA	18	16	18

In Table J.13, the yearly fuel consumption is given for the second operational year.

Table J.13: Case study 3, yearly fuel consumption (T)

Operation	***#0***	***#1***	***#2***
Fuel non-SECA	HSFO	VLSGO	HSFO
Non-SECA consumption	7851	7277	8322
Fuel SECA	ULSGO	ULSGO	HSFO
SECA consumption	498	557	637

In Table J.14, the cumulative NPC are given for each year. The data is corresponding to Figure 9.5. The applied discount rate is 5%.

Table J.14: Case study 3, total NPC (M$)

Year	***#0***	***#1***	***#2***
2020	2.9	4.1	48
2021	5.9	8.3	8.4
2022	8.9	12.4	11.8
2023	11.7	16.4	15.2
2024	14.5	20.3	18.4
2025	17.0	23.8	21.4
2026	19.6	27.5	24.4
2027	22.2	31.0	27.3
2028	24.6	34.4	30.0
2029	26.9	37.7	32.7
2030	29.1	40.7	35.2
2031	31.3	43.8	37.4
2032	33.4	46.7	39.5
2033	35.4	49.6	41.6
2034	37.3	52.3	43.5
2035	39.1	54.7	45.3
2036	40.8	57.2	47.8
2037	42.5	59.5	50.1
2038	44.1	61.8	52.4
2039	45.7	64.0	54.6

In Table J.15, a breakdown of the total life-cycle costs is given. In those data, the discount rate is set to 0% to get insight in the real costs.

Table J.15: Case study 3, breakdown of life-cycle costs (M$)

	#0	***#1***	***#2***
CAPEX	0	0	5.64
OPEX	2.95	2.97	5.21
VE	71.86	102.24	78.66

In Table J.16, a breakdown of the CAPEX is given. In those data, the discount rate is set to 0% to get insight in the real costs.

Table J.16: Case study 3, breakdown of capital expenses (M$)

	#0	***#1***	***#2***
CAPEX engines	0	0	0
CAPEX abatement tech.	0	0	4.87
CAPEX financing	0	0	0.77

In Table J.17, a breakdown of the OPEX is given. In those data, the discount rate is set to 0% to get insight in the real costs.

Table J.17: Case study 3, breakdown of operational expenses (M$)

	#0	***#1***	***#2***
OPEX engines	2.77	2.76	2.77
OPEX fuels	0.19	0.21	0.19
OPEX abatement tech.	0	0	2.24

In Table J.18, a breakdown of the voyage expenses is given. In those data, the discount rate is set to 0% to get insight in the real costs.

Table J.18: Case study 3, breakdown of voyage expenses (M$)

	#0	***#1***	***#2***
VE fuel	71.86	102.24	78.44
VE loss of revenue	0	0	0.22

K

Case study 3: sensitivity data

In this appendix, the data used in the sensitivity analysis of the second case study is given. Table K.1 shows the data of the sensitivity analysis on the scrubber price, corresponding to the payback times shown in Table 9.8.

Table K.1: Case study 3, sensitivity analysis on the scrubber price (M$)

Scrubber price	***#2, discount rate 0%***	***#2, discount rate 5%***
-40%	86.55	53.02
-20%	87.62	54.02
0%	88.69	55.01
+20%	89.76	56.00
+40%	90.83	56.99

Table K.2 shows the data of the sensitivity analysis on the price of low sulphur oils, corresponding to Figure 9.9.

Table K.2: Case study 3, sensitivity analysis on the low sulphur oil price (M$)

LS price	***#0***	***#1***	***#2***
-20%	38.96	51.84	52.09
-10%	45.23	58.09	53.41
0%	45.67	64.34	54.72
+10%	46.08	70.58	56.03
+20%	46.49	76.55	57.21

Table K.3 shows the data of the sensitivity analysis on the combined parameter variation of the low sulphur oil price and the scrubber price, corresponding to Figure 9.10.

Table K.3: Case study 3, results of the proportional relationship between the low sulphur oil price and the scrubber price (M$)

LS price	***Scrubber price***	***#0***	***#1***	***#2***
-20%	-20%	42.83	49.87	50.12
-10%	-10%	44.25	57.11	52.43
0%	0%	45.67	64.34	54.72
+10%	+10%	47.06	71.56	57.01
+20%	+20%	48.46	78.52	59.18

Table K.4 shows the data of the sensitivity analysis on the combined parameter variation of the low sulphur oil price and the scrubber price, corresponding to Figure 9.11.

Table K.4: Case study 3, results of the inverse proportional relationship between the low sulphur oil price and the scrubber price (M$)

LS price	***Scrubber price***	***#0***	***#1***	***#2***
-20%	+20%	46.75	53.79	54.04
-10%	+10%	46.20	59.06	54.38
0%	0%	45.67	64.34	54.72
+10%	-10%	45.11	69.61	55.06
+20%	-20%	44.45	74.60	55.26

L

Validation

In this chapter, the calculations made in the tool will be validated by comparing the results with existing research projects. The ship used in the second case study is a typical ship to which more often cases studies are conducted. Therefore, the validation of the tool is done with a Colour class containership. Ships in other case studies are too exceptional to compare with case studies from other researches. The validation will be done for both the scrubber business case and the LNG business case. The input parameters on itselves are already validated by using data from previous researches and actual quotations. Besides that, an average of different sources is taken in order to use substantiated and validated data.

Table L.1 gives the results of the second case study compared with two additional researches. Important to note is that the payback time is calculated without discounted costs. The research of Zis et al. gave their results with a discount rate of 5%. Those figures are calculated backwards to the results without discounted costs. The results of all three case studies are comparable. The major difference is that the calculations for the case studies of the Germanischer Lloyd an Zis et al. start already in 2015 and 2013. In those cases, the 2020 sulphur cap is not accounted, which has a major influence on the payback time. The counter effects that might have prevented the payback time of the Colour class case study to drop, is the additional engineer that is taken into account in combination with a lower ship speed and a decreased fuel efficiency.

Table L.1: Comparison of scrubber business case

Parameter	***Colour class***	***Germanischer Lloyd [98]***	***Zis et al. [165]***	
Ship type	Containership	Containership	Containership	-
Capacity	2256	2500	3500	TEU
Ship speed	15	20	16	knots
Installed power	19,700	16,000	20,500	kW
Average spread HSFO - ULSGO	264	250	230	$/T
Starting year	2021	2015	2013	-
Payback time	26	23	24	months

Table L.2 gives the results with respect to the LNG business case of the second case study compared with two additional researches. The payback time of the Colour class case study is clearly more pessimistic as for the other two case studies. The payback period of the Colour class that is represented in Table L.2 exceeds the lifetime of the ship and is extrapolated. Compared to the case study from the Germanischer Lloyd, the size of the ship is comparable. However, two significant differences are the gas tank capacity related to the endurance and the average spread between ULSFO and LNG that are taken into account. The gas tank capacity is a major contributor to the required initial capital investments. The fuel price spread taken by the Germanischer Lloyd is almost 7 times as big as in the Colour class study. This explains the major difference between the two case studies. The case study of Balland is another ship type. However, the results look very comparable. The price spread used by Balland is slightly more than twice the price as used in the Colour class case study, which contributes together with a higher tank capacity to an almost five times longer payback time for the Colour class case study.

Table L.2: Comparison of LNG business case

Parameter	***Colour class***	***Germanischer Lloyd [98]***	***Balland [9]***	
Ship type	Containership	Containership	Tanker	-
Capacity	25,175	± 25,000	51,500	DWT
Ship speed	15.2	20.0	13.5	knots
Installed power	19,700	16,000	11,540	kW
Average spread ULSGO - LNG	44	302	98	$/T
Starting year	2021	2013	2014	-
Gas tank capacity	3343	800	1500	m^3
Endurance	13,350	2650	5150	nm
Payback time	551	23	111	months

For the LNG business case, the parameters used in the case study of the Colour Class deviates significant from the parameters used in the other case studies that are used as reference. Therefore, an additional validation is required. The input data of the case study from the Germanischer Lloyd is substituted into the tool of this research to check if the payback period will be comparable. As calculations done in this thesis require a lot of input data, only the primary influencing factors are changed. The parameters that are changed are the ship speed and installed power, average price spread ULSGO - LNG, gas tank capacity. The payback time that resulted was 26 months, which is close to the outcome of the original case study from the Germanischer Lloyd. The somewhat higher payback time is explainable, as the calculations from this thesis includes more influencing factors such as the insurance costs and additional crewing costs.

M

List of specialists contacted

In the course of this project, in-depth interviews are conducted with specialists from the industry, listed in Table M.1.

Table M.1: Specialists whom contributed to the project

Name	***Company***	***Subject***
Arnout, Jonas	Seatrade Reefer Chartering N.V.	Operations research
Boer, Bert de	Seatrade Groningen B.V.	Technical fleet data
Boere, Jac	Aon	Insurance
Centeno, Miguel	Seatrade Reefer Chartering N.V.	Operational fleet data
Cisek, Jarek	Seatrade Groningen B.V.	Technical fleet data
Delcroix, Chris	ExxonMobil Petroleum & Chemical	Fuels
Dykstra, Clarence	Seatrade Reefer Chartering N.V.	Fuels
Eia, Bjarne	Harris Pye Engineering	Scrubbers
Eising, Gerard	Marine Service Noord	LNG systems
Gersen, Sander	DNV GL	Market data
Hombergh, Jan van den	ExxonMobil Petroleum & Chemical	Fuels
Kana, Austin	Delft University of Technology	Decision making
Schaap, Michael	Titan LNG	LNG
Steege, Reinier van der	Marine Service Noord	LNG systems
Westerhof, Jelle	Yanmar Europe B.V.	Dual fuel engines and SCR systems
Zwaard, Johan	Seatrade Reefer Chartering N.V.	Speed optimization

N

Paper

Sensitivity analysis on the payback periods of different emission compliance methods

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In the upcoming years, shipowners have to make far-reaching decisions on which route to be followed in order to ensure emission compliance in a cost-efficient manner. This paper examines the sensitivity of different cost categories on the payback periods of different onboard emissions compliance methods. The results will give shipowners grip on the dominating cost categories and allow them to concentrate their attention to the primary influencing factors with respect to risk mitigation.

Introduction

The International Maritime Organization [IMO] regulates the engine emissions from the exhaust gas from ships. Annex VI of the International Convention for the Prevention of Pollution from Ships [MARPOL Convention] deals with the emissions in the exhaust gas (Lindstad, Sandaas, & Stromman, 2015). In 2020, the maximum sulphur content in the exhaust gas will be reduced from 3.5% to 0.5% to regulate the Sulphur Oxides [SO_x] (IMO, 2008). A limit of 0.1% sulphur is already enforced inside Emission Control Areas [ECAs] in 2015 and will remain in effect (Lindstad, Rehn, & Eskeland, 2017). The Nitrogen Oxide [NO_x] emissions depend on the keel laying date of the ship. Ships with a keel laying date after 1 January 2011 need to comply with Tier II requirements, which basically means a NO_x reduction of 15% for slow speed Diesel engines, compared to the Tier I benchmark. Ships with a keel laying date after 1 January 2016 need to comply with Tier III requirements when sailing inside ECAs, which means a reduction of 80% compared to Tier I (IMO, 2008). The strategy on CO_2 reduction is still in development by the IMO. While relative minor measures such as the Energy Efficiency Design Index [EEDI] and Ship Energy Efficiency Management Plan [SEEMP] already exist, the pathway for major CO_2 reduction measures has still to be adopted. An initial strategy will be introduced at the 72th meeting of the Maritime Environmental Protection Committee [MEPC], which will be held in April 2018 (IMO, 2018). Possible CO_2 measures are the implementation of a carbon tax and bunker levies.

There are three alternatives currently available on the market that can be used to comply with the SO_x and NO_x regulations: (1) use low sulphur fuels, (2) install sulphur scrubber and/or catalytic reduction systems, or (3) use Liquefied Natural Gas [LNG] as a fuel (Kana, Knight, Sypniewski, & Singer, 2015). While all three alternatives are potential solutions for compliance, they each face operational, technological and economic challenges (Balland, Erikstad, Fagerholt, & Wallace, 2013).

Case study

The three main compliance options have been examined in a case study by Van der Meer (2018). The ship that is considered is a geared specialized reefer containership, which has a capacity of 2256 Twenty Foot Equivalent Units [TEU] and 672 reefer plugs. The intended lifetime of the ship is 25 years. The ship's main particulars are given in Table 1.

Table 1
Main particulars case study

Length over all	185.0 m
Breadth moulded	30.0 m
Design draft	9.00 m
Deadweight at design draft	22,380 DWT
Speed at design draft	18.9 kn
Installed ME power	13,100 kW
Installed AE power	6,600 kW

The ship is operating on a worldwide trade, sailing from Europe to New Zealand and back. During a 12 weeks lasting roundtrip, the ports *Rotterdam* – *Dunkirk* – *Radicatel* – *Papeete* – *Noumea* – *Nelson* – *Napier* – *Tauranga* – *Pisco* – *Paita* – *Philadelphia* – *Zeebrugge* – *Tilbury* – *Rotterdam* are called. Containerships are in general typed by short port calls and relatively high sailing speeds (Gu & Wallace, 2017). This is also reflected in this case study, the ship spent only 13% in port and sails with an average speed of 15.2 knots. The Sulphur Emission Control Area [SECA] coverage is only 12% of the sailing time.

The fuel price scenario that is used is based on both historical data and future predictions. The interrelation between fuel benchmarks and marine fuels is derived from historical data. The Brent index is used as benchmark for oils. The United Kingdom [UK] National Balancing Point [NBP] is used as benchmark for natural gas. The interrelation between the fuel benchmarks and marine fuels is assumed to be constant. The future prediction of the Brent benchmark is an average of the outlooks from the US Energy Information Administration (2017), UK Gov. Department for Business (2017) and the World Bank (2017). The future prediction of the UK NBP benchmark is an average of the outlooks from the World Bank (2017), Statista (2018) and the UK Gov. Department for Business (2017). The price scenario of the marine fuels that is used in the case study is given in Figure 1.

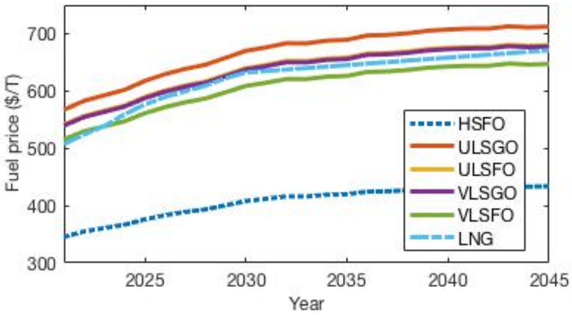

Figure 1. Fuel price scenario (Van der Meer, 2018)

The fuel prices as shown in Figure 1 represent the actual fuel prices without correction applied for the difference in energy content. The energy content in the fuel is usually expressed by the calorific value in MJ/kg. Table 2 gives the calorific values that are used in this case study.

Table 2
Calorific value of the fuels (Witherby Seamanship, 2013)

HSFO	40.0 MJ/kg
ULSGO	42.7 MJ/kg
ULSFO	40.0 MJ/kg
VLSGO	42.7 MJ/kg
VLSFO	40.0 MJ/kg
LNG	49.2 MJ/kg

In the calculations of the case study, more influencing factors and aspects are included than that is done with other researches. The model of Van der Meer (2018) includes the primary influencing costs such as equipment costs, installation costs and fuel costs. Besides that, secondary influencing costs are included such as insurance costs, maintenance costs, crewing costs, costs of sludge disposal, costs of consumables and loss of revenue are included. Especially the costs of insurance may add up for dual-fuel installations, as the insurance costs are usually proportional increasing with the value of the installation (Van der Meer, 2018). But also crewing costs are contributing to the feasibility of both scrubbers and dual-fuel installations. For a scrubber, an additional engineer is accounted in the calculation for operation and maintenance of the scrubber. For the dual-fuel installation, additional courses needs to be taken by the crew to be able to operate equipment using low flashpoint fuels.

Breakdown of costs

Generally, the expenses from a ship are categorized (Van der Burg et al., 2014). The total life-cycle costs can be broken down in three types: capital expenses [CAPEX], operational expenses [OPEX], and voyage expenses [VE]. The capital expenses include the investment costs required for the purchase and installation of the engines and related equipment, and abatement techniques. If other types of financing are used rather than equity, finance costs are also included in this category, which are basically the costs of interest (Van der Meer, 2018). The capital expenses are always charged to the shipowner (Stopford, 2009). The operational expenses include the running costs of the ship that are independent of the voyage, but dependent on a vessel being active or not. Typical operational expenses are maintenance costs, crew salaries, insurance costs and costs of consumables (Van der Burg et al., 2014). In this analysis, distinction has been made between engine related operational expenses, fuel related operational expenses and operational expenses related to abatement techniques. The operational expenses are in case of a bareboat charter agreement charged to the charterer, otherwise they will be charged to the shipowner (Stopford, 2009). The voyage expenses are the costs directly associated with sailing the vessel on a certain trade. Voyage expenses influencing the total life-cycle cost related to the emission compliance methods are the fuel costs and loss of revenue (Van der Meer, 2018). Port charges and possible future carbon taxes are also part of the voyage expenses, but neglected in this case study. Port charges are not accounted because the discount is very uncertain and often retroactively defined. Carbon taxes are not yet enforced but might be a possible measure to reduce CO_2 emissions. The voyage expenses are in case of a bareboat charter agreement or a time charter agreement charged to the charterer, otherwise they will be charged to the shipowner (Stopford, 2009).

A summarized breakdown of the total life-cycle costs is given in Figure 2.

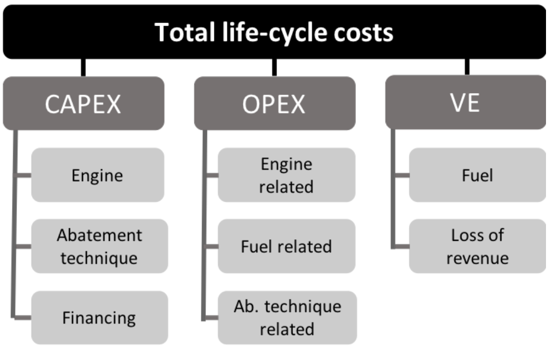

Figure 2. Breakdown of emission related life-cycle costs

Scrubber business case

The nominal payback period of a scrubber is obtained by comparing this compliance option to a reference case. The propulsion plant in the reference case will consist of a Diesel engine without any abatement technique installed. This means that the ship in the reference case is forced to burn low sulphur fuels: fuel with a maximum sulphur content of 0.1% inside SECAs and fuel with a maximum sulphur content of 0.5% outside SECAs (IMO, 2008). The ship with a scrubber installed is allowed to burn high sulphur fuel oil in both areas. The total life-cycle costs related to emission compliance are for the reference case 181.3 $M\$$, for the entire lifetime of the ship. For the case with a scrubber installed, the total life-cycle costs are reduced with almost 25% to 137.8 $M\$$. These are the nominal costs, meaning that the costs are not discounted through time. Figure 3 gives the share of each cost category for both cases, which shows that the voyage expenses are in both cases dominant. The installation of a scrubber leads to increased capital and operational expenses and decreased voyage expenses.

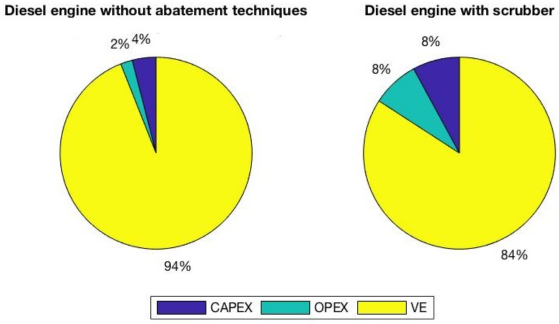

Figure 3. Breakdown of costs, scrubber comparison

In the reference case, 10,757 T of fuel is consumed per year, of which 9470 T VLSGO outside SECAs and 1287 T ULSGO inside SECAs. There is distillate fuel used instead of residual fuel because the price discount on residual fuel compared to distillates is only 5.5%, while the energy content of distillates is 6.5% higher. Despite the fact that distillates are encountering some additional consumable costs, the running costs of distillates are still lower than for residuals. The case where a scrubber is installed consumes a total of 11,596 T HSFO, of which 10,194 T outside SECAs and 1402 T inside SECAs. The increased amount of consumed fuels is mainly due to the difference in calorific value. Besides that, the specific fuel consumption will rise with 1% due to the power required for pumps and an increased back-pressure of the exhaust gas from the engine (Hansen, 2012).

A variation of parameters will be applied to each cost category in the first level of breakdown of the total life-cycle costs. Figure 4 gives the first sensitivity analysis where a variation on the capital expenses has been applied. The parameter variation is applied from 0% to 200% of the capital expenses from the case study. This means that 100% on the x-axis indicates the original payback time, which was 3 years. As can be seen in the graph, the payback periods are rounded up. The trendline gives an approximation of the exact payback periods.

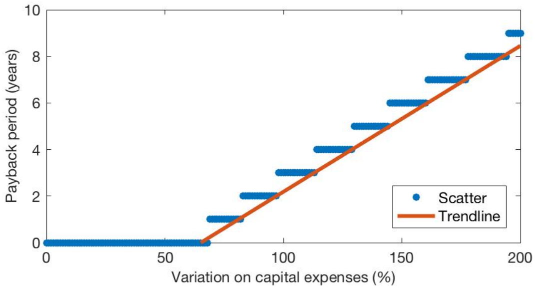

Figure 4. Sensitivity of the capital expenses on the scrubber payback period.

Figure 4 shows that a variation on the capital expenses from 0% to 70% results in the case where the total emission related capital expenses from the ship with a scrubber will be less than the capital expenses of the reference ship. This situation is not realistic to happen at all, but validates the results in a logic manner. Furthermore, a linear relationship is observed between the variation on capital expenses and the payback period of the scrubber. There should be clarified that the variation on capital expenses is done on the total capital expenses including the costs of the engines and the costs of the abatement techniques. Financing is not included. The variation of parameters is only done on the case where the scrubber is installed. The parameters of the case without scrubber installed is kept unchanged.

Figure 5 gives the results of the sensitivity analysis where a variation on the operational expenses has been applied. The parameter variation is applied from 0% to 200% of the operational expenses from the case study. The first observation is that a drastically change of the operational expenses only results in a change of up to 1 year. Similar to the variation of capital expenses, the payback period changes linear to the change of operational expenses.

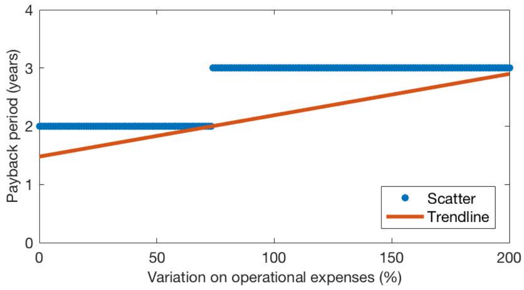

Figure 5. Sensitivity of the operational expenses on the scrubber payback period.

Figure 6 gives the results of the sensitivity analysis where a variation on the voyage expenses has been applied. The parameter variation is applied from 0% to 200% of the voyage expenses from the case study. The effects of the variation on the voyage expenses are more radical compared to the effects of both the variation on the capital expenses and the variation on the operational expenses. Even the relationship of the payback period and the variation on voyage expenses is not linear but increasing rapidly when increasing the voyage expenses compared to the base case. A 38% increase of the voyage expenses results already in unaffordable payback periods. Therefore, there can be concluded that the payback period is most sensitive to a variation of the voyage expenses.

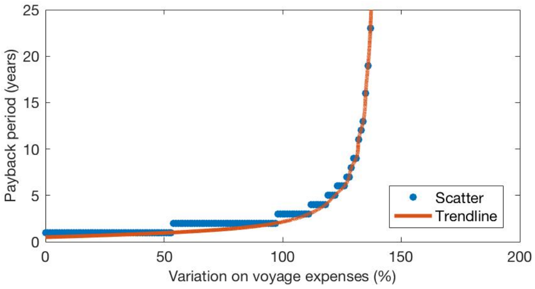

Figure 6. Sensitivity of the voyage expenses on the scrubber payback period.

Dual-fuel business case

The nominal payback period of a dual-fuel engine including gas tanks, equipment and installation is obtained by comparing this compliance option to a reference case. The propulsion plant in the reference case consists of a Diesel engine with a Selective Catalytic Reduction [SCR] system. The Diesel engine with NO_x after-treatment is chosen as reference case because the dual-fuel engine has the benefit of reducing also NO_x emissions, a benefit which a scrubber does not have. The ship in the reference case is forced to burn low sulphur fuels, while the ship fitted with dual-fuel engines can burn either low sulphur fuels or LNG, whichever fuel is cheaper. The total life-cycle costs for the reference case are 185.6 M\$ for the entire lifetime of the ship. For the case with a dual-fuel engine installed, the total life-cycle costs are increased with 4% to 193.8 M\$. This means that in the results of the initial case study, the dual-fuel installation will not be payed back within the lifetime of the ship. Figure 7 gives the share of each cost category for both cases, which show that the capital expenses are significant larger for the dual-fuel engine compliance option.

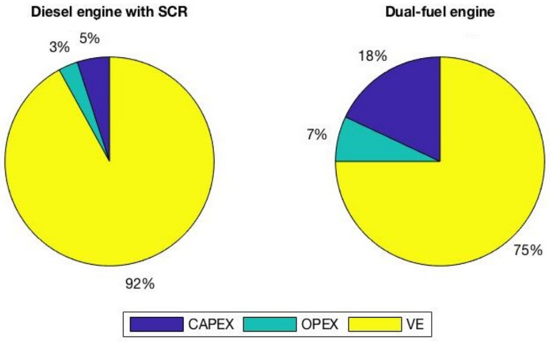

Figure 7. Breakdown of costs, dual-fuel engine comparison

In the reference case, 10,863 T of fuel is consumed per year, of which 9563 T VLSGO outside SECAs and 1300 T ULSGO inside SECAs. The case where a dual-fuel engine is installed consumes 9260 T LNG, of which 8136 T outside SECAs and 1124 T inside SECAs. The reduced fuel consumption is mainly caused by a larger calorific value of the LNG compared to oils.

A variation of parameters will be applied to each cost category in the first level of breakdown of the total life-cycle costs. Figure 8 gives the sensitivity analysis where a variation on the capital expenses has been applied. The parameter variation is applied from 0% to 100% of the capital expenses from the case study. The payback period with the parameters used in the case study exceeds already the lifetime of the ship. An increase of the expenses turned out to have no added value, because this would only result in longer payback periods. Similar to the scrubber business case, a linear relationship between the capital expenses and the payback period of the dual-fuel system is observed. A variation on the capital expenses from 0% to 25% results in the case where the total emission related capital expenses from the ship with a dual-fuel engine will be less than the capital expenses of the reference case, which is unrealistic.

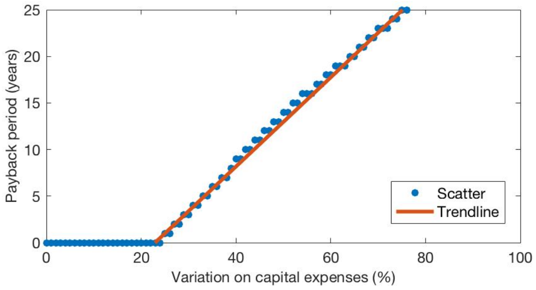

Figure 8. Sensitivity of the capital expenses on the payback period of a dual-fuel installation.

Figure 9 gives the results of the sensitivity analysis where a variation on the operational expenses has been applied. The parameter variation is applied from 0% to 100% of the operational expenses from the case study. It shows that the effects of a variation on operational expenses are marginal. Only a reduction of more than 60% will result in payback periods that do not exceed the lifetime of the ship.

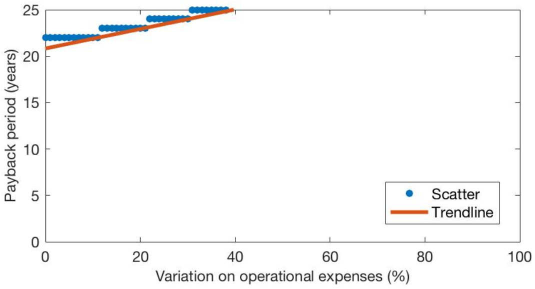

Figure 9. Sensitivity of the operational expenses on the payback period of a dual-fuel installation.

Figure 10 gives the results of the sensitivity analysis where a variation on the voyage expenses has been applied. The parameter variation is applied from 0% to 100% of the voyage expenses from the case study. A non-linear relationship between the voyage expenses and payback period is observed, similar to the scrubber business case. Within the realistic boundaries of the parameter variation, up to 20% reduction of the voyage expenses, the payback periods remain relatively high.

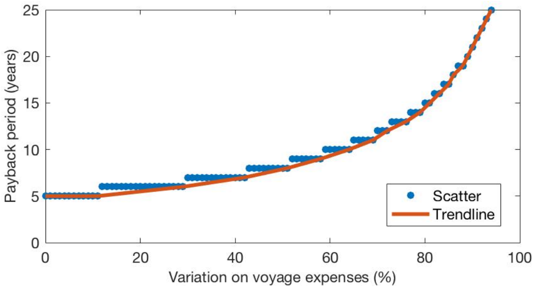

Figure 10. Sensitivity of the voyage expenses on the payback period of a dual-fuel installation.

Conclusions

This paper has investigated the influences of different cost categories on the payback periods of different emission compliance methods for ships. The influences of the capital expenses, operational expenses and voyage expenses in general has been examined by a variation of parameters compared to an existing case study. The existing case study is performed by Van der Meer (2018) on a to be built specialized reefer containership of $22,380$ DWT. The ship is operating on a 12 weeks roundtrip from Europe to New Zealand and sails with an average speed of 15.2 knots. The installed power, including main and auxiliary engines, is 19,7 MW.

The initial payback period of a scrubber is 3 years. NO_x compliance is not considered in this respect, as this does not influence the payback time of the scrubber. The average fuel spread between high sulphur fuel oil and 0.5% sulphur distillates that is used is 229 $/T. This value is not corrected for the difference in calorific values of both fuels. The variation of parameters shows a linear relationship between the payback period and both the capital expenses and operational expenses. As the quantity of operational expenses is relatively limited, this cost category has hardly influence on the payback time. The primary influence on the payback time of a scrubber is found to be caused by a variation of the voyage expenses. An increase of more than 38% of the voyage expense results already in unaffordable payback periods.

The initial payback period of a dual-fuel engine exceeds the lifetime of the ship, which is 25 years. The reference case includes the installation of a Selective Catalytic Reduction system, as a dual-fuel engine has the advantage of being NO_x Tier III compliant. The average fuel spread between LNG and 0.5% sulphur distillates that is used is 13$/T. This fuel spread is not corrected for the difference in calorific values of both fuels. The variation of parameters of this business case results in comparable results to the sensitivity applied to the scrubber business case. A linear relationship is observed between the payback period and both the capital expenses and operational expenses, which where more significant for the capital expenses. A variation on the voyage expenses shows high sensitivity, which means that the focus should be on this cost category with respect to risk mitigation.

Acknowledgements

This paper has been made possible by the support of Seatrade Groningen B.V. and Seatrade Reefer Chartering N.V.

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