Study on the Technical Implementation of Carbon Capture Onboard Ships

Master of Science in Marine Technology Thesis

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Allseas

Study on the Technical Implementation of Carbon Capture Onboard Ships

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Preface

This thesis was conducted to obtain the master's degree in Marine Technology with the specializations in Marine Engineering and Ship and Offshore Structures at the Delft University of Technology. It was performed in collaboration with Allseas Engineering.

I would like to thank Elena De Lazzari for her inestimable support throughout this project. Her expertise and guidance have definitely helped me to achieve the best outcome for this thesis. I also want to thank her for her level of involvement in this project, providing me with extremely useful feedback on very short notice.

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Finally, I want to thank my family, my girlfriend and my friends, both from Delft and Barcelona, for their support, not only during this thesis but throughout the whole master's degree. I feel immensely fortunate to have them by my side.

Roger Segura Casals
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Abstract

The maritime sector CO_2 emissions are one of the contributors to the increase of the concentration of this gas in the Earth's atmosphere. One of the proposed solutions for reducing these emissions is the implementation of carbon capture technologies onboard vessels. Carbon capture technologies work on the principle of apprehending the carbon dioxide resultant of any chemical process, avoiding the need to emit it into the atmosphere.

The goal of this study is to obtain a general solution to the technical challenge of implementing carbon capture technologies onboard ships. To do so, a general model is developed for the implementation of carbon capture onboard vessels regardless of their characteristics or operational profile. To test the model, two case studies are performed based on real vessels from the company *Allseas* where, using the developed model, a capture system design is proposed for each ship. With the input of one of these case studies and the developed model, the effect that the characteristics of the vessel's engines and the characteristics of the capture system have on the capture process is analysed.

The results from the case studies show that the proposed designs can reduce the CO_2 emissions by 28% for the first case study and by 21% for the second case study. This reduction is enough to comply with the short-term objectives of the IMO in terms of CO_2 emissions reduction.

The results of the characteristics analysis reveal that LNG is the preferred fuel to be used in combination with carbon capture. Small carbon capture systems have a higher performance in vessels with 2-stroke engines whereas larger carbon capture systems have a higher performance with 4-stroke engines. For the post-capture refrigeration cycles, a similar effect is observed. Small capture systems have a higher performance with absorption refrigeration cycles and large capture systems have a higher performance with vapour-compression refrigeration cycles. The reason for these results is the fact that the performance of the capture process mainly depends on the heat requirement of the capture system.

Thanks to the results of the analysis, it is found that, by combining the use of LNG and the implementation of carbon capture, a more significant reduction of the CO_2 emissions for each case study can be achieved. This reduction is equal to 53% for the first case study and 46% for the second one.

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Nomenclature

Abbreviations

Abbreviation	Definition
% wt.	Concentration in weight
ABS	American Bureau of Shipping
Abs	Absorption Refrigeration Cycle
B100	Biodiesel
CC	Carbon Capture
ETS	Emission Trading System
EU	European Union
Exh	Exhaust
FO	Ultra Low Sulfur Fuel Oil
GHG	Greenhouse Gasses
HFO	Heavy Fuel Oil
HX	Heat Exchanger
IMO	International Maritime Organisation
L/G	Liquid to Gas ratio in a column
LNG	Liquefied Natural Gas
LHV	Lower Heating Value
MDO	Marine Diesel Oil
MEA	Monoethanolamine
MEPC	Marine Environment Protection Committee
MeOH	Methanol
MGO	Marine Gas-Oil
TEU	Twenty-foot Equivalent Unit
Vap-Comp	Vapour-Compression Refrigeration Cycle
VC	Vapour-Compression Refrigeration Cycle

Chemical Formulation

Formulation	Compound
CO	Carbon Monoxide
CO_2	Carbon Dioxide
H_2	Molecular Hydrogen
H_2O	Water
NH_3	Ammonia
NOx	Nitrogen Oxides
O_2	Molecular Oxygen

1 Introduction

1.1. Background

During the past 250 years, the majority of mankind has increasingly become more and more dependent on the heat produced by the combustion of fossil fuels. This has resulted in an exponential increase of the human-originated CO_2 emissions to the atmosphere [2]. As a consequence, the concentration of carbon dioxide in the troposphere has surpassed the regular levels of the last million years [3–7]. This concentration increase has accentuated the naturally occurring greenhouse effect that resulted in a rise of the average atmospheric temperature of 1.5°C during the past 250 years [8] and could result in a further increase of 6.4°C by the end of the 21st century [9]. This temperature surge has already caused some registered effects such as the melting of the Arctic ice layer and it is expected that it will increase the probability of extreme meteorological events such as hurricanes [10].

1.1.1. Decarbonisation of the world's fleet

The use of watercraft is partly responsible for this increase of the CO_2 levels in the atmosphere. Only maritime transport accounts for around 3% of the total global carbon dioxide emissions [11]. This does not account for all the other economic activities that make use of vessels, like fishery or offshore construction. This means that the impact of ships in the CO_2 emissions is larger than this 3%. Different institutions have started to propose and develop new policies and strategies to reduce these emissions.

The International Maritime Organisation (IMO) developed an initial strategy to reduce greenhouse gas emissions in 2018 [12] that has been updated in 2023 [13]. The most significant decisions taken were to reduce the maritime transport industry CO_2 emissions by 20% by 2030, by 70% by 2040 and reach net zero emissions by 2050 compared to the emissions level in 2008 [13].

The European Parliament, the Council of the European Union and the European Commission agreed to include vessel-related activities in the European Union Emission Trading System (EU ETS) in 2024. This means that the vessels must buy GHG emission rights from this EU ETS in order to be allowed to call in EU ports. This requirement will be progressively implemented for cargo vessels starting with 40% of the ship's emissions and ending with 100%. In 2027, all vessels with a gross tonnage larger than 5000 tons whose activities are offshore-related will also need to comply with this rule [14].

To achieve this decarbonisation of the world fleet, different solutions have been proposed. They can be divided into three groups: modifying the design and operation of the vessel to improve its energy efficiency, using other energy sources than fossil fuels or blocking the CO_2 from being emitted to the atmosphere.

The first group of methods are usually based on modifying already existing vessels or building new ones without significant innovations in their design to improve their efficiency. For example, the use of the exhaust gas waste heat to increase the overall efficiency [15], the optimisation of the design of the propulsion system [16] and the hull's shape design [17] or the reduction of the vessel's operational speed also known as slow steaming [18], among others. These methods have not been largely implemented due to the combination of not having economic incentives to be applied [19] and the fact that the CO_2 reduction they suppose is not very substantial as their potential emission reduction is below 10% in most cases [20]. Other basic methods have been implemented to a greater extent, like smart lighting [21], but their impact on the total reduction of CO_2 emissions is not very significant either.

An example of the implementation of these methods can be found in the announcement of the company *Allseas Engineering* of the hybridisation of three of their vessels by implementing batteries. This will allow a more efficient power generation by running their diesel generators to their optimal load, reducing the CO_2 emissions [22].

The second group of suggested solutions is the use of alternative fuels. These fuels have been proposed as an alternative hence, the name, to the conventional fuels used currently in the maritime industry, such as Heavy Fuel Oil (HFO) or Marine Diesel Oil (MDO), in order to reduce GHG emissions of ships [23]. Within this group, there are different compounds that are considered alternative fuels.

The first group are carbon-free fuels, like hydrogen (H_2) [24] or ammonia (NH_3) [25] which fully eliminate the CO_2 emissions due to their zero-carbon composition as long as they are produced using green energy. However, they have different drawbacks like their low energy density [26], their storage conditions [27] or the increase of NOx emissions [28].

As an example of this carbon-free fuel implementation, the company *Eidesvik* is currently modifying one of its supply vessels so it can perform long-distance trips powered only by ammonia fuel cells [29].

The second group are renewable carbon-containing fuels, like methanol (MeOH) [30] or bio-fuels [23]. They are considered net zero CO_2 emissions if they are produced using atmospheric CO_2 [31, 32].

The implementation of these new fuels in the maritime sector would drastically reduce the emissions of CO_2, especially for H_2 and NH_3. Nonetheless, there are different challenges to this implementation such as redesigning the whole vessel's energy generation system to accommodate the use of these fuels or the increase in size and complexity of the fuel storage [33]. The current production limit of these fuels also directly affects the availability to bunker them in most of the ports in the world [33].

Finally, the third group of solutions available for reducing the emissions of the world's fleet are those that avoid the emission of the CO_2 to the atmosphere by capturing and storing it onboard [34]. This group of solutions are known as carbon capture (CC) technologies. Their working principle is to separate the CO_2 from the other components in which this carbon dioxide is mixed with [35]. Once this CO_2 is isolated, it is transported and sent to permanent storage sites, such as depleted gas or oil fields [36]. Additionally, it can also be used in any other process that requires this compound, such as enhanced-oil recovery systems [36], greenhouse agriculture [37] or synthetic fuel production [38].

Carbon capture technologies have been implemented or are currently being studied in some other CO_2 emission-intensive industries. These include power generation in the coal-fired power plants Boundary Dam or Petra Nova [39] or cement production in the CEMCAP or CLEANKER projects [40].

1.1.2. Carbon capture onboard vessels

There are several reasons why carbon capture technologies have attracted the attention of the maritime industry and might become more suitable for CO_2 abatement than the other proposed solutions.

Firstly, post-combustion CC can be retrofitted fairly easily in already existing CO_2-producing plants without requiring a large redesign or without considerably affecting their operational performance [41]. This is an asset as it would allow already existing ships to be outfitted with these technologies.

Secondly, as mentioned previously, design and operational measures are not expected to reach the CO_2 reduction levels required for the new policies and strategies [17]. However, CC technologies are estimated to be capable of reducing up to 65% the emissions of GHG [42]. This means that a significant reduction in the CO_2 emissions can be potentially achieved by implementing CC only. Additionally, if other design and/or operational measures are also implemented, this cutback can be larger.

Thirdly, the onboard implementation of some CC technologies is predicted to reach maturity and commercial viability earlier than the implementation of alternative fuels in vessels, which requires more extensive research [43]. This means that CC could be a short/mid-term method to reduce the emissions of the vessels that still use conventional fuels until the implementation of zero-carbon fuels.

Fourthly, on the same topic of alternative fuels, some of them, such as the mentioned MeOH or biofuels but also others like synthetic methane, still have carbon in their composition. This means that CO_2 will still be produced. CC could be the solution to keep part of this carbon dioxide onboard which could be disposed of onshore to produce more fuel. This, combined with direct air CC, would close this carbon loop without a net positive CO_2 emission to the atmosphere. So, in a long-term perspective, CC might be a useful technology after the phasing-out of conventional fuels.

Finally, related to this CO_2 disposal, carbon dioxide can be seen as a valuable good from which to obtain revenue [44] not only for synthetic fuel production but for other uses. This would mean that CC is a CO_2 abatement method that could partially or fully return its initial investment and operation expenses [44]. This feature is shared with most design and operational measures as they usually aim for fuel-saving, which could be also seen as a cost-reduction method [43].

Despite all these positive aspects, there are also some drawbacks that impede the implementation of CC onboard ships. For instance, the required power for the current CC systems is usually very high [45] which results in an increase in fuel consumption and, therefore, the cost of CC. Additionally, the capture system and the CO_2 storage require a considerable amount of onboard space, meaning that the implementation of a CC might impact significantly the operation of the vessel, reducing the cargo space or the work capabilities of the ship [46].

1.2. Literature review

After determining that carbon capture can be a potential method for decreasing the CO_2 emissions of the world's fleet, a review of the published literature regarding this topic is performed. This is done by determining the existing carbon capture technologies and which are their characteristics. This is followed by an examination of the studies that researched the implementation of CC onboard ships. Finally, a review of the onboard CO_2 storage methodologies is executed. The objective of this review is to determine the preferred characteristics of the capture system for its implementation onboard ships as well as to establish what important aspects of this topic have not been considered in the literature.

1.2.1. Carbon capture technologies

Among the carbon capture technologies currently being studied and commercially available, there are four groups: pre-combustion, post-combustion, oxy-combustion and chemical looping.

The pre-combustion method consists in the decarbonisation of the fuel before combusting it. The hydrocarbon is broken apart using molecular oxygen (O_2) or water (H_2O) and it is transformed in CO_2 and molecular hydrogen (H_2) that can be then combusted. Its advantages are its low energy requirement and small system size [45]. Its main drawback is its high operation cost [47].

The post-combustion method consists of the separation of the CO_2 present in the gas resulting from the combustion of hydrocarbon fuels, also called flue gas or exhaust gas. Its main advantages are its operational flexibility and the easiness to retrofit it in existing plants [48]. Its main drawbacks are the high energy requirement and its large system size [47].

The oxy-combustion method consists in the capture of the CO_2 after the combustion of the fuel in an oxygen-rich environment. This is done by separating the oxygen from the air in a previous step. Its main advantages are its simplicity in separating the CO_2 [48] and its elimination of NO_x production [47]. Its main drawback is its high energy consumption during the O_2 separation [47].

The chemical looping method consists of using a metal-metal oxide pair which is cyclically reduced and oxidised using the fuel and air creating H_2O, CO_2 and energy [49]. It has the same advantages as the oxy-combustion method plus it has a lower energy requirement [48]. Its main disadvantage is the choice of metal-metal oxide pair to make the system cost-effective [48].

Figure 1.1 depicts a schematic explanation of how these CC technologies work.

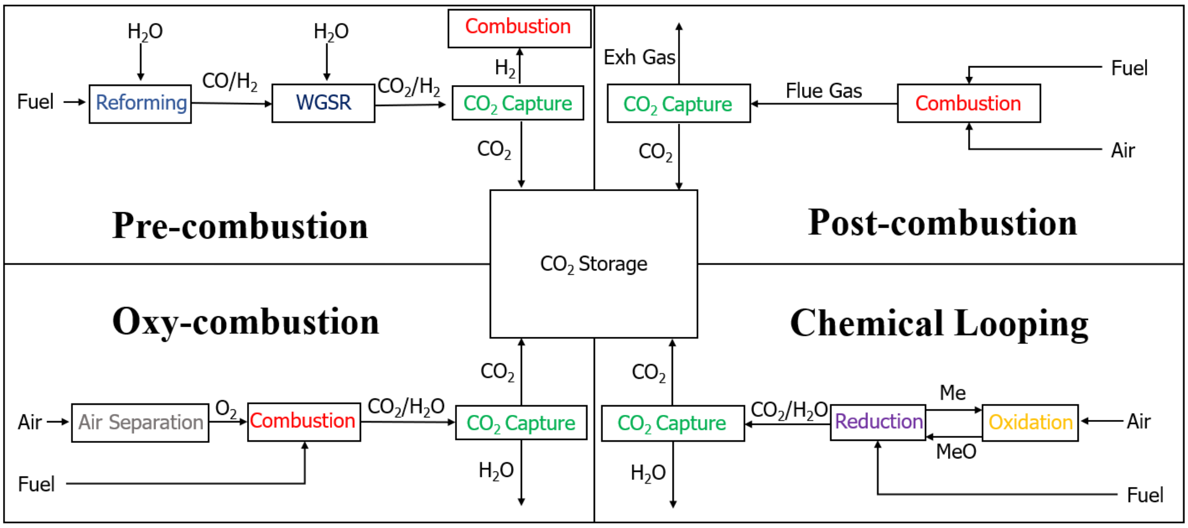

Figure 1.1: Schematic diagrams of the four groups of carbon capture technologies

Knowing the characteristics of the different carbon capture groups, it is decided to focus only on those technologies that are applicable for the post-combustion group since they are, at this moment, the only feasible methods to be applied, either in the construction of new ships or the retrofitting of already built ones [50]. The reason for this is that post-combustion systems can be fitted within ships without significantly modifying how the propulsion and electric power are generated since it is applied after the combustion process. Moreover, the space and energy requirements for this group of technologies are viable for the majority of vessels.

Post-combustion carbon capture technologies

Regarding the post-combustion CC method, there are several technologies proposed. Table 1.1 summarises the most relevant ones along with their working principle and their advantages and drawbacks.

Table 1.1: Characterisitcs of the post-combustion CC technologies [45, 47, 51–64]

CC Technology	Working Principle	Advantages	Disadvantages
Chemical Absoprtion	Chemically reacting the CO_2 using a solvent	- High capture capacity at low CO_2 concentration - Most commercially mature technology	- High thermal energy requirement -High escape/ degradation rate
Physical Absorption	Physically diluting the CO_2 using a solvent	- Lower energy requirement than chemical absorption - Different desorption methods	- High pressure and low temperature requirements for absorption
Adsorption	CO_2 adherence to an adsorbent material	- Optimal adsorbent selection due to the large range of available materials - Different desorption methods	- Low CO_2/N_2 selectivity -Low stability
Membrane	CO_2 separation using selective permeation	- No regeneration energy or chemicals required - Compact size	- Selectivity/permeability trade-off - Non-possibility to take advantage of waste heat - Susceptibility to impurities/water
Cryogenic	CO_2 separation by different phase change temperature of gases	-Very high purity and capture ratio - No need for compression/ refrigeration after separation	- High electric energy requirement - Non-possibility to take advantage of waste heat -Susceptibility to impurities/water
Hydrate	Molecular trapping using crystalline formations	- No extra chemicals required -High ratio CO_2/hydrate - Easiness to recover the CO_2 by depressurising the hydrate	- High pressure and low temperature requirement for hydrate formation - Non-possibility to take advantage of waste heat - Lack of commercial maturity
Hybrid	Combination of CC technologies	- Enhance advantages and compensate disadvantages of the used technologies	- Complexity increase of the CC system

1.2.2. Implementation of carbon capture on vessels

With the most significant post-combustion CC technologies described, their application on ships is studied. An analysis of the academic research on the topic is performed along with a short inquiry into the new regulations for the implementation of CC onboard.

The majority of the studies focused on the implementation of CC onboard are based on the modelling of a CC system included in the energy generation plant of a vessel and analysing the results of this model [43, 46, 60, 65–67]. A second group of studies took the research a step forward by including a comparison between different characteristics of the vessel/capture system like the fuel or the solvent used for the CO_2 capture [68–71]. The third group of studies performed a comparison between the performance of the CC process against other CO_2 mitigation techniques like speed reduction or exhaust gas recirculation [17, 42, 72, 73]. Finally, two studies focused on determining how the implementation of CC would affect the Energy Efficiency Design Index of the vessel studied [74, 75].

From these studies, two outcomes can be extracted. The first one is the confirmation that CC can become a feasible method for CO_2 emissions reduction of ships. This is because the results of these studies show a capture rate between 50% and 90% of the produced CO_2.

The second outcome extracted is that there is a general preference for using chemical absorption technology for the implementation of CC onboard ships. As mentioned in table 1.1, this technology works by chemically reacting the CO_2 with a solvent. This is done in an absorption column where the exhaust gas is fed at the lower part of the column and it is sprayed with the solvent on its way up. Then, the CO_2-rich solvent is heated in a desorption tower to reverse the reaction and separate the captured CO_2. Regarding the solvent used, the reviewed studies show a preference for using a 30% wt. aqueous solution of Monoethanolamine (MEA).

The reason behind this technology choice is the fact that MEA chemical absorption offers the highest capture capabilities of all the other technologies mentioned in table 1.1 for the low partial pressure in which the CO_2 is produced onboard vessels.

Apart from the conventional absorption column used for the capture process, another capture technology for onboard application is being considered. This technology is called membrane contactor and it is a hybrid between membrane separation and chemical absorption. Its working principle is locating the exhaust gas on one side of a hollow membrane and the MEA solution on the other side. Then, thanks to the chemical affinity between the CO_2 and the MEA, the carbon dioxide separates from the exhaust gas and gets captured by the MEA. The advantage that this technology has over the conventional absorption column is the reduction of the required space due to the membranes' high contact surface.

Regarding the new regulations for the implementation of CC onboard, the American Bureau of Shipping classification society published in December of 2022 a set of rules [76] that deal with the aspects that concern this implementation: design, construction, installation and survey of all the systems and their equipment that are involved in the CO_2 capture process. These rules focus on the application of the chemical absorption CC systems, however, they also consider other technologies for post-combustion capture like membranes or cryogenic and even for CC different capture strategies such as pre-combustion capture.

These rules are related to the certification that all the equipment and machinery dedicated to the CC process do not pose any hazard to the vessel, the crew or the environment. This means that they do not aim to make the capture system efficient. However, having this regulation serves as a reference point for some design choices that may involve some kind of danger onboard.

1.2.3. CO_2 storage onboard

Once the CO_2 is captured, it must be stored onboard until the vessel can unload it. This means that a post-capture stage needs to be included in the capture system. The goal of this stage is to change the thermodynamic conditions of the captured CO_2 in order to make its storage as effective as possible. The main parameter that dictates these conditions is its density. This is because, the higher the density, the higher amount of carbon dioxide that can be stored onboard in the same volume. At normal conditions of 1 atm and 25°C, CO_2 is a gas with a very low density of 1.8 kg/m^3.

Based on the characteristics of the different CO_2 phases, it is decided to focus on the liquid phase storage since it is the one that offers high density [77] (600 times larger than at normal conditions) and it allows pumping the CO_2 through pipes, easing the transport process. This decision matches with all the studies performed on the topic of CO_2 storage onboard vessels [78–97].

To reach these liquefaction conditions, the CO_2 needs to be cooled. To do so, there are different refrigeration cycles that can be used. Based on the results of the aforementioned studies, it is decided that the more suitable refrigeration cycle for the post-capture CO_2 liquefaction process is the vapour-compression cycle using ammonia with storage conditions of 15 bar and -30°C. The reason for choosing this combination of refrigeration cycle and conditions is the lower electric energy requirement compared to all the other cycles/conditions.

Despite this, the studies also show that the absorption refrigeration cycle could potentially improve the results of the vapour-compression cycle onboard ships in certain cases. A brief explanation of the working principle of the vapour-compression and absorption cycles can be seen below. Figure 2.2 depicts them in a schematic manner.

The vapour compression cycle is based on cooling the CO_2 to its condensation temperature by evaporating the refrigerant fluid. During the evaporation stage, the refrigerant extracts the thermal energy from the CO_2 reducing its temperature. In this cycle, the refrigerant goes through 4 different stages: compression, condensation, expansion and evaporation [98]. For the compression stage, multi-stage compression is used since it increases the efficiency of the refrigeration cycle [80]. It includes a refrigerant cooler in between the compression stages.

The absorption refrigeration cycle is a refrigeration cycle very similar to the vapour compression cycle but whose primary energy source is thermal energy instead of electric power. To do so, instead of using a compressor to raise the pressure of the refrigerant, an absorption cycle is implemented [83]. The working principle is the same as the chemical absorption CC technology previously explained.

The main advantage of this cycle versus the vapour compression one is the fact that thermal energy is used as the main driver for the process instead of electricity. This, for the case of vessels, could be an asset to be exploited by using the waste heat of the exhaust gas [83].

1.2.4. Literature review conclusions and research gaps

After completing this literature review, different conclusions can be extracted. The first one is the reviewed studies prove that CC can become a feasible method for mitigating the CO_2 emissions of ships due to its potential high capture rate. The second conclusion is that, at this point in time, chemical absorption using MEA is the preferred CC technology to be implemented onboard ships. This is because it is the technology that has the highest capture capabilities than any other capture technologies for the conditions in which the CO_2 is produced onboard vessels (low partial pressure).

In terms of the CO_2 storage, the preferred conditions are the liquid phase at 15 bar and -30°C. To achieve these conditions, the literature reviewed endorses the use of the vapour-compression refrigeration cycle with ammonia as a refrigerant. This is because the combination of these conditions with this refrigeration cycle has the lowest energy requirement of the combinations studied.

Apart from the aspects that the literature reviewed has shed light on the topic, two main research gaps can be also identified. The first one is the lack of a method for implementing carbon capture onboard vessels regardless of the vessel's characteristics and operational profile. This is because all the reviewed studies performed this implementation focusing only on specific cases. This general model is deemed necessary as it would facilitate the analysis of the suitability of implementing CC onboard depending on the ship's particularities ship without requiring a tailored model for each case.

The other gap that has been identified is the lack of an analysis of the effect that the different characteristics of the vessel's power generation plant and the capture system have on the overall CO_2 capture performance. Some of the studies performed certain comparisons between specific parameters, like Monteiro et al. [68] or Einbu et al. [70] that compared the CC system performance between using marine diesel oil and liquefied natural gas as fuel. Despite this, there is no comparison that includes different types of engines or capture technologies, for example. This analysis is important as it would establish which specific features should each vessel/capture system have in order to maximise the performance of the capture process.

1.3. Research objectives

After analysing the outcomes of the literature reviewed and its research gaps, the main research objective for this study is to obtain a general solution to the technical challenge of implementing carbon capture technologies onboard ships. To do so, two objectives are set that, if accomplished, will provide this general solution.

The first objective is to develop a method for calculating the technical parameters that are relevant for the CC implementation onboard any ship, regardless of its characteristics and operational profile. These relevant parameters are the CO_2 emissions reduction achieved, the extra fuel consumption resulting from the CC implementation and the required space onboard the vessel for allocating the capture system. Fulfilling this objective would result in eliminating the need for developing custom-made carbon capture systems, easing the study of their implementation onboard ships.

The second objective is to establish how the technical characteristics of the vessel's power generation plant / CO_2 capture system affect the performance of the carbon capture process onboard ships. The importance of accomplishing this objective is that it would allow determining in which conditions these characteristics enhance the performance of the capture process.

1.4. Research methodology

To accomplish the proposed objectives, the following methodology is used. First, a general model for the implementation of carbon capture onboard ships is developed. Different characteristics are modelled within the model namely, two types of engines (2-stroke and 4-stroke), five fuels, two carbon capture technologies and two post-capture refrigeration cycles. The required inputs for this model are generic data that can be obtained for any vessel i.e.: its engines' characteristics (engine type, rated power and fuel used) and the vessel's operational profile. Then, depending on these input parameters and the capture system characteristics, the model calculates and outputs a set of data with several capture system designs with their own CO_2 emissions reduction, extra fuel consumption and onboard space requirement.

Next, two case studies are performed on two different vessels owned and operated by the company *Allseas*. Each case study is performed in the following way. First, the required data from the vessel is input into the developed model. Then, one of the proposed designs output by the model is selected. The criteria for this selection is maximising the CO_2 reduction while making sure that the design is feasible in terms of energy and space requirements. The goal of these case studies is to prove that the developed model is capable of providing two feasible capture systems for two different vessels without requiring any custom-made modification.

Then, an evaluation of the performance of the capture process for each combination of engine type, fuel, capture technology and refrigeration cycle modelled in the developed model is executed. To do so, each combination is input into the model along with the operational profile from one of the case studies. After that, the performance of each combination is analysed depending on the capture system size and compared with the other combinations. The goal of this analysis is to fulfil the second research objective of determining how these combinations of characteristics affect the overall performance of the capture process.

Finally, using the results of the analysis, modifications to the original characteristics of the case studies are proposed in order to improve the performance of the capture process.

2

System Modelling

The general model for carbon capture implementation onboard ships consists of a mathematical model of a physical carbon capture system embedded in an iterative cycle that determines the amount of CO_2 that can be captured given the characteristics and operational profile of a certain vessel and for different types of fuel used, namely: marine gas-oil (MGO), ultra low sulfur fuel oil (FO), liquefied natural gas (LNG), methanol (MeOH) and biodiesel (B100). Additionally, it also calculates the increase in fuel consumption resulting from the power requirements of the equipment of the capture system. The required space onboard to allocate the whole system is also calculated depending on the amount of captured CO_2.

The explanation for needing the iterative process and how it works can be found in Appendix A.1 but, in short terms, it makes sure that the extra electric power required to operate all the capture system is also taken into account in the model.

Finally, the operation of the proposed systems by the model is assumed to be constant in terms of amount of CO_2 captured. A variable operation of the capture system was not introduced in the model as the effects of operating a system below its design operation point were not studied in this thesis.

2.1. Capture system description

The capture system's model consists of three stages: pre-capture, capture and post-capture stages. Figure 2.1 depicts the general layout of the capture system.

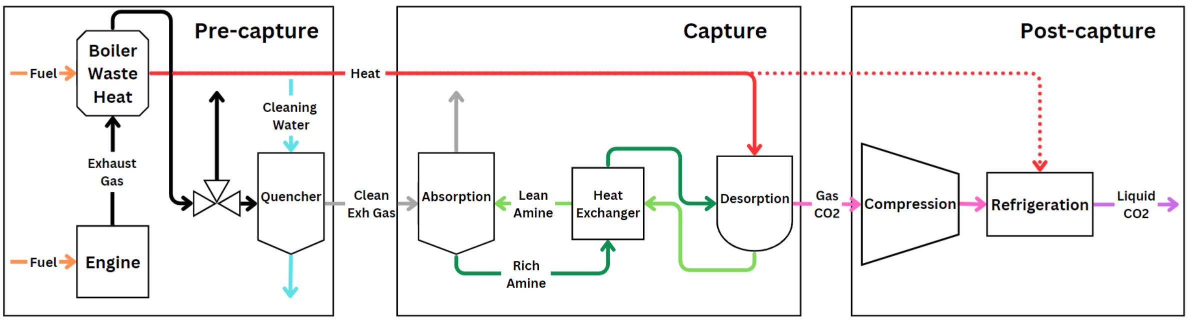

Figure 2.1: Simplified diagram of the CO_2 capture system

The pre-capture stage includes three elements: the vessel's engines, a marine composite boiler and a quencher column. The engines' model determines the fuel and exhaust gas mass flow rate, temperature and CO_2 concentration based on the engines' power, the type of fuel used and the operational profile of the ship. The composite boiler consists of a heat exchanger that absorbs the thermal energy of the exhaust gas after it has exited the turbocharger and a burner that produces extra heat on demand. This burner works with MGO regardless of the fuel burnt in the engines. Finally, the quencher is a washing column where the exhaust gas is sprayed with water to cool it and remove solid impurities.

For the capture stage, the model includes two alternative absorption elements both based on chemical absorption using an aqueous solution of MEA at 30% wt. The first one is an absorber column where the exhaust gas is sprayed with the MEA solution to dissolve the CO_2 in the exhaust gas. The second element consists of a hollow-fibre membrane contactor where the exhaust gas and the MEA solution are located on each side of the membrane and the CO_2 flows from the exhaust gas to the MEA solution through the membrane. The reason for modelling both elements is to propose an improvement to the conventional absorption column. After the absorption stage, the CO_2-rich MEA solution is then fed into a desorber column where it is heated using the heat extracted in the pre-capture stage, forcing the CO_2 to dissociate from the solution. The CO_2-lean solution is then fed back into the absorption component.

The post-capture stage aims to liquefy the captured CO_2 to reduce its volume in order to increase the quantity that can be stored onboard. To do so, two elements constitute this stage: a compression stage that rises the CO_2 pressure and a refrigeration cycle that cools the carbon dioxide below its condensation temperature. For this last refrigeration step, the model includes three cycles: a conventional ammonia vapour-compression cycle, an ammonia absorption refrigeration cycle and, for those vessels whose engines run with LNG, a heat exchanger that uses the fuel evaporation to cool the CO_2. The reason for modelling these three cycles is to determine which one is more suitable for each case since each cycle has its pros and cons. Figure 2.2 depicts the three implemented refrigeration cycles.

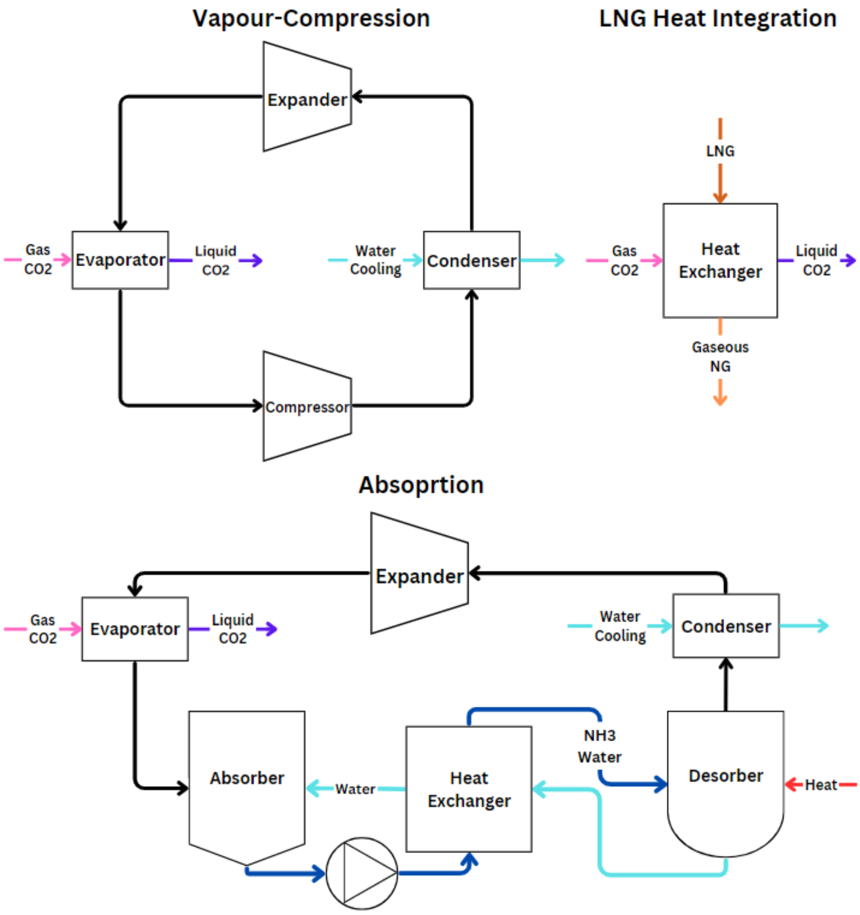

Figure 2.2: Simplified diagram of the three modelled refrigeration cycles

2.2. Pre-capture stage modelling

The model's first stage aims to obtain the necessary features of the vessel's engines and the characteristics of the exhaust gas. The required inputs are the rated power and number of strokes per cycle of each engine as well as the fuel used.

Using curve fitting on the data provided by marine engine manufacturers, namely *Wärtsilä* and *MAN*, different mathematical functions were derived. These functions give the engines' specific fuel consumption as well as the exhaust gas temperature and CO_2 concentration of each operation point of the engine based on the input parameters. The mathematical functions obtained by the curve fitting are depicted graphically in Appendix A.2.

Finally, by combining the input data and the function-based parameters, the remaining characteristics are calculated using the following equations:

$$\dot{m}_f = P_{eng} \cdot Load \cdot SFC \tag{2.1}$$

$$\dot{m}_{CO_2} = \dot{m}_f \cdot CO_{2ratio} \tag{2.2}$$

$$\dot{m}_{exh} = \frac{\dot{m}_{CO_2}}{[CO_2]} \tag{2.3}$$

where:

- $\dot{m}_f$: Engine's fuel mass flow rate [kg/s]
- P_{eng}: Engine's rated power [kW]
- $Load$: Engine's loading point [%]
- SFC: Engine's specific fuel consumption [kg/(kJ)]
- $\dot{m}_{CO_2}$: Exhaust CO_2 mass flow rate [kg/s]
- CO_{2ratio}: Mass ratio between the CO_2 produced and the fuel burnt
- $\dot{m}_{exh}$: Exhaust gas mass flow rate [kg/s]
- $[CO_2]$: Exhaust CO_2 concentration [% wt.]

The fuels' CO_{2ratio} is specified in table 2.1 and were obtained from the IMO's MEPC.281(70) resolution [99] and Coronado et al. [100].

Table 2.1: CO_{2ratio} of each fuel [99, 100]

Fuel	**HFO**	**MGO**	**LNG**	**MeOH**	**B100**
CO_{2ratio}	3.114	3.206	2.75	1.375	2.838

Once the necessary parameters of the exhaust gas are gathered, the model proceeds to calculate the amount of thermal energy available in the exhaust gas. For this purpose, a composite boiler based on the Alfa Laval Aalborg OC-TCi [101] is modelled with a waste heat recovery module that absorbs the thermal energy from the exhaust gas by reducing its temperature to 165ºC using equation 2.4. This temperature was chosen as it is assumed that the boiler works with steam at 6 bar which has an evaporation temperature of around 160ºC and a pinch temperature of 5ºC. The value of the specific heat capacity of the exhaust gas depends on its temperature and it is obtained using data from *Aspen Hysys*.

$$Q_{whr} = c_{p_{exh}} \cdot \dot{m}_{exh} \cdot (T_{exh} - (T_{steam} + T_{pinch})) \tag{2.4}$$

where:

- Q_{whr}: Available heat for CO_2 capture [kW]
- $c_{p_{exh}}$: Specific heat capacity of the exhaust gas (Range: 1.075-1.15) [kJ/(kg·ºC)]
- T_{exh}: Exhaust temperature after the turbocharger [ºC]
- T_{steam}: Steam temperature in the waste heat boiler [ºC] (160ºC in the model)
- T_{pinch}: Pinch temperature between the exhaust gas and the steam [ºC] (5ºC in the model)
- Q_{vessel}: Required heat for the vessel operation [kW]

In addition to the recovered heat from the exhaust gas, the modelled composite boiler also includes an MGO-fired steam generation system in order to increase the available heat for the CO_2 capture. This feature allows the operation of the capture system in the design condition throughout the operational profile of the vessel. This is because it provides the required extra heat during those situations where the waste heat of the exhaust gas does not allow for the operation at the design point of the capture system. However, its first downside is the fuel consumption increase since the boiler requires MGO to operate. The second one is the fact that, for achieving this certain amount of extra heat, the boiler needs to burn fuel which, at its turn, produces more CO_2. This means that the entirety of this extra heat is not dedicated to the capture of CO_2 originated in the engines but only a fraction of it. The other fraction is to capture the extra CO_2 originated in the boiler. Equation 2.5 depicts the fraction of the extra energy used to capture the CO_2 originated in the boiler considering the lower heating value and the CO_2 ratio of MGO and the required thermal energy to capture the CO_2 expressed in table 2.2.

$$f_{boil} = \frac{h_{abs} \cdot CO_{2ratio}}{LHV_{MGO} \cdot \eta_{boil}} = 0.4544 \tag{2.5}$$

where:

- f_{boil}: Fraction of energy used to capture the CO_2 originated in the boiler [-]
- h_{abs}: Thermal energy required to capture a unit mass of CO_2 [MJ/kg]
- LHV: Lower heating value of the MGO [MJ/kg]
- η_{boil}: Boiler efficiency [-]

Table 2.2: Model parameters for the boiler's energy fraction dedicated to capture the CO_2 from the boiler itself

h_{abs}	CO_{2ratio}	LHV_{MGO}	η_{boil}
5.125 MJ/kg_{CO_2} [1]	3.206 kg_{CO_2}/kg_{MGO}	42.7 MJ/kg_{MGO} [99]	86.325 % [101]

With the extra energy required for the capture system known, Equation 2.6 is used to calculate the required mass flow rate of fuel for the boiler.

$$\dot{m}_{fboil} = \frac{Q_{extra}}{LHV \cdot \eta_{boil}} \tag{2.6}$$

where:

- $\dot{m}_{fboil}$: Boiler's fuel mass flow rate [kg/s]
- Q_{extra}: Extra heat used for CO_2 capture [kW]

[1] The way this value is obtained is explained later in the text

The amount of CO_2 and exhaust gas produced in the boiler is calculated using equations 2.2 and 2.3. In this case, the CO_2 ratio for MGO is the one stated in table 2.1. The flue gas CO_2 concentration was determined using the fuel, air and flue gas mass flow data provided by [101] which has a constant value of 15.73 %.

With the heat recovered from the exhaust and the extra heat produced in the oil-fired boiler, the total available heat for the CO_2 capture can be obtained using equation 2.7.

$$Q_{tot} = Q_{whr} + Q_{extra} \tag{2.7}$$

Nonetheless, not all of this energy can be used for the capture system. The reason is that the desorption temperature of the capture stage is around 120.5 ºC whereas the hot well temperature of the steam system is 80 ºC. This means that only the energy from cooling the water from 160ºC to 125ºC and the latent heat of condensation can be used for the capture system. This fraction represents around 92% of the total steam energy, as seen in equation 2.8. The remaining 8% is assumed to be used in the other thermal requirements of the vessel. If these thermal requirements were higher than this 8%, the available heat for CO_2 capture would decrease, as shown in equation 2.9

- If $Q_{ship} \leq 0.08 \cdot Q_{tot}$

$$Q_{av} = 0.92 \cdot Q_{tot} \tag{2.8}$$

- If $Q_{ship} > 0.08 \cdot Q_{tot}$

$$Q_{av} = 0.92 \cdot Q_{tot} - (Q_{ship} - 0.08 \cdot Q_{tot}) \tag{2.9}$$

where:

- Q_{tot}: Total heat produced [kW]
- Q_{av}: Available heat for the capture process [kW]
- Q_{ship}: Heat requirements of the vessel (model input) [kW]

The last step in the pre-capture stage is the quenching process of the exhaust gas that will pass through the absorption stage. To obtain the fresh water required for this process, a reverse-osmosis fresh water generator is modelled based on the *Wärtsilä* reverse osmosis fresh water generators [102]. To determine the optimal washing water/exhaust gas ratio (L/G), several simulations in *Aspen Hysys* were conducted. The results show that, assuming a washing water temperature of 25ºC, a minimum L/G of 2.5 is required in order to cool the exhaust gas enough (around 25ºC) so that the CO_2 absorption process stays at its maximum efficiency (around 93.2%).

This water temperature was assumed because it is 5ºC higher than the average temperature of the sea surface [103], giving a certain safety margin. This is because, if the water temperature at the exit of the freshwater generator is colder, the operational L/G could be reduced to maintain the exhaust gas temperature before the absorber. If the washing water was assumed colder in the design stage, the capture efficiency would decrease in the case that the water temperature resulted to be higher.

2.3. Capture stage modelling

As mentioned previously, the proposed model includes two different systems to separate the CO_2 from the exhaust gas: the MEA absorption column and the membrane contactor systems. In this section, the modelling of both systems is explained

2.3.1. MEA absorption column system

The design of this capture system is based on one of the designs proposed by Monteiro et al. [68] with some modifications. The main modification is the precooling stage of the exhaust gas before the absorber. In the model proposed by Monteiro et al., the exhaust gas has a temperature of 40ºC whereas in this model, this temperature does not go further than 25ºC. This decrease in the temperature results in an increase of the capture efficiency of the absorber. Table 2.3 depicts the relevant set of input parameters of the capture system of both studies.

In order to confirm that the model proposed worked properly, a check with the input values of the design proposed by Monterio et al. was performed. The outputs show very similar results meaning that the proposed model worked accurately as can be seen in table 2.3.

Table 2.3: Design parameters of the capture stage

	Parameter	This Model	Monteiro et al. [68]	Monteiro check
Loading [mol CO2/MEA]	Lean	0.253	0.25	0.252
	Rich	0.496	0.5	0.504
Absorber	L/G	1.3	1.39	1.39
	Solvent T_{in} [ºC]	52.5	40	40
	Exh Gas T_{in} [ºC]	25.05	40	40.2
	Solvent T_{out} [ºC]	27	50	48.3
	Pressure [bar]	1	1	1
	Capture Eff. [%]	93.2	80	81.3
Desorber	Solvent T_{in} [ºC]	95	100	100
	Solvent T_{out} [ºC]	120.5	120	119.2
	Pressure [bar]	2	2	2

With the available heat known, the amount of CO_2 that can be captured using the aforementioned capture design is obtained. The required thermal energy to capture 1 kg of CO_2 is 5125 kJ. This value was obtained by averaging the results from different simulations of the model in *Aspen Hysys* under different conditions of exhaust temperature and it shows a good agreement with the value obtained by Monteiro et al. [68] and Ros et al. [43]. The values for these simulations are depicted in appendix A.3. The largest deviations between the results obtained and the average value do not differ more than 200 kJ/kg. This means that the average value depicts accurately the energy required for the CO_2 capture.

After obtaining the captured CO_2 mass flow rate, the total amount of exhaust gas that is required to flow through the absorber to apprehend this CO_2 is calculated using equation 2.10.

$$\dot{m}_{exhAbs} = \frac{\dot{m}_{CO_2Cap}}{[CO_2] \cdot \eta_{Cap}} \tag{2.10}$$

where:

- $\dot{m}_{exhAbs}$: Exhaust gas mass flow rate through the absorber [kg/s]
- $\dot{m}_{CO_2Cap}$: CO_2 mass flow rate captured [kg/s]
- η_{Cap}: Absorber CO_2 capture efficiency [%] (93.2% in the model)

Once the exhaust gas mass flow rate through the absorber is determined, the mass flow rate of the MEA solvent through the capture system is calculated using the previously mentioned absorber L/G ratio of 1.3.

The electric power for the pumps and blower of the capture system is determined using equations 2.11 and 2.12. Table 2.4 provides the required head for each pump. These required heads were determined knowing that the columns (quencher, absorber and desorber) have a height of 8 meters. To account for the pressure losses around the circuit, an extra 1-2 meters of extra head were introduced. This safety margin was obtained based on the results of different *Aspen Hysys* simulations. The reason why the rich pump head is larger than the other two is the fact that the operating pressure of the desorber is 2 bar, therefore requiring a higher pump head.

$$P_{pump} = \frac{\dot{m} \cdot H_{req} \cdot g}{\eta_{pump}} \tag{2.11}$$

where:

- P_{pump}: Required electric pump power [W]
- $\dot{m}$: Liquid mass flow rate [kg/s]
- H_{req}: Required pump head [m]
- g: Earth's gravitational constant (9.81 m/s^2)
- η_{pump}: Pump efficiency [%] (including hydraulic and mechanical loses)

Table 2.4: Required head of each pump

Pump	**Quencher Pump**	**Lean Pump**	**Rich Pump**
H_{req}	10 m	10 m	19 m

$$P_{blow} = \frac{\dot{m}_{exhAbs} \cdot \Delta p_{blow}}{\rho_{exh} \cdot \eta_{blow}} \tag{2.12}$$

where:

- P_{blow}: Required electric blower power [kW]
- Δp_{blow}: Blower pressure increase (20 kPa in the model)
- ρ_{exh}: Exhaust gas density (around 0.7961 kg/m^3)
- η_{blow}: Blower efficiency [%] (including all losses)

2.3.2. MEA membrane contactor system

The second absorption system is a membrane contactor based on the design proposed by Chabanon et al. [104]. In the referenced study, different materials were tested to determine which one provides the best separation process both in terms of the amount of CO_2 and the durability of the membrane. The material chosen for this study is a combination of a microporous polypropylene hollow fibre membrane coated with a dense skin of polymethylpentene.

The reason behind choosing this material combination is that, thanks to the polymethylpentene coating, the pore-wetting effect (i.e.: the solvent filling the membrane pores and reducing its capture efficiency) is completely avoided. This makes the membrane durable for a longer period of time, if compared with using a polypropylene hollow fibre membrane without coating. The main negative aspect of using polymethylpentene coating is the reduction of the CO_2 mass transfer coefficient across the membrane, resulting in a bigger membrane size to achieve the same capture.

In terms of the implementation of this absorption system in the model, all the data provided in table 2.3 is also used since the desorption process remains the same, independent of the absorption element chosen. Using the data from table 2.3 and the membrane contactor characteristics provided by [104], a modular membrane contactor system design is proposed. This design provides the same CO_2 absorption as the column element described previously. This means that the proposed design does not aim to improve the capture efficiency of the column system, which is significantly high (93,2 %) but to reduce the required space for allocating the absorption system. The proposed design parameters of one module are depicted in table 2.5.

Table 2.5: Design parameters of the membrane contactor module

Exhaust Gas Flow	**Membrane Height**	**Membrane Diameter**	**Co2 Flux Density**	**Capture Area**	**Capture Efficiency**
1 kg/s	2.4 m	0.6 m	0.032 g/m^2·s	2330 m^2	93,2 %

In addition to the space reduction, this modular membrane contactor system also improves the operational flexibility of the capture system. In the case of the absorption column, the change in the operational conditions of the vessels (eg.: from transit to anchor conditions) could affect the effectiveness of the capture system since the column is only designed for a specific exhaust gas mass flow rate. On the other hand, the presence of different membrane contactor modules makes it possible to operate only the required number of modules for each specific condition, keeping the effectiveness constant. However, this change in the operational point of the capture system is not considered in this study.

2.4. Post-capture stage modelling

With the captured CO_2 mass flow rate known, the first step in the post-capture stage is to compress the CO_2. To do so a double-stage compression is modelled with water cooling in between the stages. To determine the electric power required for it, equation 2.13 is used.

$$P_{comp} = c_{p_{gas}} \cdot \dot{m}_{gas} \cdot (T_{out} - T_{in}) \tag{2.13}$$

where:

- P_{comp}: Required electric compressor power [kW]
- $\dot{m}_{gas}$: Gas mass flow rate [kg/s]
- $c_{p_{gas}}$: Gas specific heat capacity (temperature dependant) [kJ/(kg·ºC)]
- T_{out}: Temperature at the compressor discharge [ºC]
- T_{in}: Temperature at the compressor suction (40ºC in the model) [ºC]

To determine the temperature at the compressor's discharge, equation 2.14 is used which takes into consideration both the pressure ratio and the polytropic efficiency of the compressor. The values of the model for the CO_2 compression can be found in table 2.6.

$$T_{out} = T_{in} \cdot \left(\frac{p_{out}}{p_{in}}\right)^{\frac{\gamma-1}{\gamma \cdot \eta_{comp}}} \tag{2.14}$$

where:

- T_{out}: Temperature at the compressor discharge [K]
- T_{in}: Temperature at the compressor suction (313.15 K in the model) [K]
- p_{out}: Pressure at the compressor discharge [bar]

- p_{in}: Pressure at the compressor suction [bar]
- γ: Gas heat capacity ratio [-]
- η_{comp}: Polytropic compressor efficiency [%]

Table 2.6: Model parameters for the CO_2 compression

CO_2 gas c_p	T_{in}	p_{in}	p_{out}	γ
0.925-1 J/g·ºC	40 ºC	1.8 bar	18.1 bar	1.12-1.26

With the CO_2 compressed, the model proceeds to calculate the refrigeration cycle characteristics in order to liquefy the CO_2. As mentioned, the model includes one refrigeration method that uses the LNG vaporisation and two refrigeration cycles that use ammonia: the vapour-compression and absorption cycles. The modelling of the systems is explained next.

2.4.1. Heat integration with LNG vaporisation

For vessels that use LNG as fuel, the refrigeration of the CO_2 can be performed by the evaporation process of the natural gas before it enters the engine. This means that the CO_2 cooling can be accomplished without any extra power requirement and it only requires a heat exchanger for the whole cooling stage. The model uses the value of the LNG mass flow calculated in the pre-capture stage to determine its cooling capacity using equation 2.15 with table 2.7 data.

$$Q_{fluid} = \dot{m}_{fluid} \cdot (c_{p_{gas}} \cdot (T_{Hgas} - T_{vap}) + h_{vap} + c_{p_{liq}} \cdot (T_{vap} - T_{Cliq})) \tag{2.15}$$

where:

- Q_{fluid}: Fluid cooling energy [kW]
- $\dot{m}_{fluid}$: Fluid mass flow rate [kg/s]
- $c_{p_{gas}}$: Gas specific heat capacity [kJ/(kg·ºC)]
- T_{Hgas}: High temperature of the gas [ºC]
- T_{vap}: Temperature of evaporation [ºC]
- h_{vap}: Latent heat of vaporization [kJ/kg]
- $c_{p_{liq}}$: Liquid specific heat capacity [kJ/(kg·ºC)]
- T_{Cliq}: Low temperature of the liquid [ºC]

Table 2.7: Model parameters for the LNG evaporation

LNG gas c_p	T_{Hgas}	T_{vap}	LNG h_{vap}	LNG liquid c_p	T_{Cliq}
2.37 J/g·ºC	35 ºC	-114.91 ºC	379.136 J/g	4.563 J/g·ºC	-120 ºC

With the LNG cooling capacity known, the cooling energy required to liquefy the CO_2 is calculated using the same equation 2.15 with the parameters stated in table 2.8.

Table 2.8: Model parameters for the CO_2 liquefaction

T_{Hgas}	T_{vap}	CO_2 h_{vap}	CO_2 liquid c_p	T_{Cliq}
40 ºC	-22.9 ºC	288.77 J/g	2.087 J/g·ºC	-25 ºC

If the cooling capacity of the LNG exceeds the cooling energy required by the CO_2 in all the operating conditions, it means that no extra cooling cycle is required onboard the vessel. On the contrary, if the LNG capacity is lower than the CO_2 requirement, then one of the two following cycles is required to reach the required capacity.

2.4.2. Ammonia vapour-compression refrigeration cycle

The first step for modelling the vapour-compression refrigeration cycle is determining the mass flow rate of ammonia required to cool and condensate the captured CO_2. To do so, equation 2.16 is used.

$$\dot{m}_{NH_3} = \frac{Q_{CO_2} - Q_{LNG}}{h_{vap_{NH_3}} \cdot (1 - \chi_{NH_3})} \tag{2.16}$$

where:

- $h_{vap_{NH_3}}$: NH_3 Latent heat of vaporization [kJ/kg]
- χ_{NH_3}: NH_3 Vapour quality at the inlet of the evaporator (0.2672 in the model) [-]

With the ammonia mass flow rate known, the next step is to determine the power of the refrigeration cycle compressor as well as the ammonia discharge temperature after the compression. To do so, equations 2.13 and 2.14 are used with the parameters indicated in table 2.9.

Table 2.9: Model parameters for the NH_3 compression

NH_3 gas c_p	T_{in}	p_{in}	p_{out}	γ
2.065-2.335 J/g·ºC	-31.74 ºC	1.1 bar	15.6 bar	1.21-1.3

2.4.3. Ammonia absorption refrigeration cycle

The second refrigeration cycle modelled is an ammonia absorption system. The system works on the same physical principle as the vapour-compression cycle: the cooling is achieved by evaporating the refrigerant thanks to a decrease in its pressure). The difference between them is the refrigerant compression step. In the vapour-compression cycle, a mechanical compressor raises the pressure of the refrigerant. For the absorption cycle, this pressure surge is achieved by dissolving the refrigerant (NH_3 in the model) in a liquid (water in the model) and then pumping the mixture of fluids. By doing this, the mechanical energy required to increase the pressure decreases significantly. After the pumping step, as can be seen in figure 2.2, thermal energy is required to separate the NH_3 and the water (regeneration process) in a separation column.

The way this cycle is modelled is by assuming that both the thermal energy required for the CO_2 desorption and the NH_3 regeneration processes come from the pre-capture stage. This means that, by using this cycle, less CO_2 can be captured as part of the thermal energy is used in the refrigeration cycle. Knowing this, the first step for modelling this cycle is to determine both mass flows rates of CO_2 and NH_3 using the system of equations 2.17 and 2.18.

$$Q_{av} = \dot{m}_{CO_2} \cdot h_{desorp} + \dot{m}_{NH_3} \cdot h_{regen} \tag{2.17}$$

$$\dot{m}_{NH_3} = \frac{(\dot{m}_{CO_2} \cdot c_{p_{gas}} \cdot (T_{Hgas} - T_{vap}) + h_{vap} + c_{p_{liq}} \cdot (T_{vap} - T_{Cliq})) - Q_{LNG}}{h_{vap_{NH_3}} \cdot (1 - \chi_{NH_3})} \tag{2.18}$$

where:

- h_{desorp}: CO_2 desorption heat (5125 kJ/kg)
- h_{regen}: NH_3 regeneration heat (4176 kJ/kg)

With both mass flow rates known, the model calculates the amount of water required to dissolve the NH_3. Through different simulations using *Aspen Hysys*, it was obtained that the optimal mass flow rate of water is around 4.35 times the flow rate of ammonia. Finally with this flow rate of the NH_3-H_2O mixture known, the required power for the pumping process can be calculated using equation 2.19.

$$P_{pump} = \frac{\dot{m}_{mix} \cdot \Delta p_{pump}}{\rho_{mix} \cdot \eta_{pump}} \tag{2.19}$$

where:

- P_{pump}: Required electric mixture pump power [kW]
- Δp_{pump}: pump pressure increase (1450 kPa in the model)
- ρ_{mix}: Mixture density (around 907.4 kg/m^3)
- η_{pump}: Pump efficiency [%] (including all loses)

For this cycle, the heat input during the regeneration process cannot be done using the steam circuit modelled in the pre-capture stage. The reason for this is the fact that the regeneration process is performed at around 200ºC. This temperature is significantly higher than the steam system one. The solution to this issue is to direct the hot exhaust gas into the regeneration column before entering the composite boiler.

2.5. Cooling modelling

Across the capture and post-capture stages different cooling steps are required, namely:

Post-capture and CO_2 compression

- CO_2 cooling and water condensation after the desorption step
- CO_2 cooling between the compression steps
- CO_2 cooling after the compression stage

NH_3 vapour-compression refrigeration

- NH_3 cooling between the compression steps
- NH_3 condensation after the compression step

NH_3 absorption refrigeration

- NH_3-water mixture cooling
- NH_3 cooling and water condensation after the regeneration step
- NH_3 condensation after the regeneration step

For all these steps, fresh water is used as the cooling fluid. To determine the mass flow rate of water required for each of these steps, the model uses equation 2.20. The water inlet and outlet temperatures are assumed to be 25ºC and 35ºC respectively. Similar to the waste heat boiler, a pinch temperature of 5ºC within the heat exchangers is assumed. This means that all the fluids exit the cooler with a temperature of 40ºC.

For the NH_3 condensation, in addition to the decrease of temperature, the cooling is also needed to condensate the ammonia, meaning that its latent heat of evaporation is added to the numerator of equation 2.20.

$$\dot{m}_{H_2O} = \frac{c_{p_{fluid}} \cdot \dot{m}_{fluid} \cdot (T_{In} - T_{Out})}{c_{p_{H_2O}} \cdot (T_H - T_L)} \tag{2.20}$$

where:

- $\dot{m}_{H_2O}$: Required water mass flow rate [kg/s]
- $c_{p_{fluid}}$: Specific heat capacity of the cooled fluid [kJ/(kg·ºC)]
- $\dot{m}_{fluid}$: Mass flow rate of the cooled fluid [kg/s]
- T_{In}: Inlet temperature of the cooled fluid [ºC]
- T_{Out}: Outlet temperature of the cooled fluid [ºC] (40ºC in the model)
- $c_{p_{H_2O}}$: Specific heat capacity of water [kJ/(kg·ºC)] (4.2 kJ/(kg·ºC) in the model)
- T_L: Water inlet temperature [ºC] (25ºC in the model)
- T_H: Water outlet temperature [ºC] (35ºC in the model)

With the required cooling water flow rates determined, the model uses equation 2.11 to determine the electric power needed for each cooling pump. In this case, the required head to overcome the pressure losses across the system is assumed to be around 0.5 bar (or an extra head of 5 m of water column) based on [105].

2.6. Space requirement modelling

The last modelling stage is estimating the size of all the pieces of equipment that compose the whole capture system. To do so, the first step is to separate the different elements depending on their location. Based on the Requirements for Onboard Carbon Capture and Storage guidelines from the classification society ABS [76], four different spaces were identified:

- Composite boiler space
- Columns space (blower, quencher, absorber, desorber and regenerator)
- Pre-capture and capture equipment space (Heat exchangers and pumps)
- Post-capture equipment and CO_2 storage space

The reason behind this separation is due to the specific position of each element or group of elements onboard. The waste heat boiler is required to be in the exhaust gas line. ABS recommends allocating the columns close to the exhaust gas line but, since their geometry varies significantly from the waste heat boiler, it is considered a different space. For the pre-capture and capture equipment, it is assumed that it will be located close to the columns space. The space occupied by the post-capture equipment and the CO_2 storage is considered to be the same as they are required to be located close to each other in order to avoid the evaporation of the CO_2 in the piping during its transfer to the storage tanks.

All the mathematical functions used for estimating the sizing of the equipment are based on the mass flow rate of the fluids that pass through the specific piece of equipment (eg.: The sizing of the desorber is based on the MEA solvent mass flow rate). These mathematical functions were obtained using curve fitting with data from different sources. In section A.4 of appendix A there are detailed the sources for all the data as well as the mathematical functions obtained. As a safety margin, 25% of the calculated space for each element is added to this calculated value to account for the extra space needed for the operation of these elements, such as maintenance or piping.

3 Case Studies

After developing the general model presented in the previous chapter, two case studies are performed to test its performance. In addition to this, the aim of these case studies is also to check that CC is indeed a feasible method for CO_2 emissions reduction for ships, as the literature reviewed shows.

3.1. Maximum CO_2 emissions reduction and feasibility criterion

Before deepening into the case studies themselves, the potential maximum CO_2 emissions reduction is investigated along with the limitations that might impede reaching this maximum reduction. This will provide a reference for which to compare the results of the case studies in order to determine the impact of these limitations. Additionally, a feasibility criterion is established to determine whether these limitations actually make the onboard CC implementation impractical.

To begin with, if all the exhaust gas is sent to the capture system, a capture rate of 93.2% could be achieved as this is the efficiency of the capture system (see table 2.3). However, this capture rate is not equal to the CO_2 emissions reduction. This is because, in order to achieve this capture rate, the CC system requires energy to operate, both electric and thermal. This energy is obtained by burning more fuel, producing more carbon dioxide. This results in a technically possible CO_2 reduction of between 85% and 90%, depending on the characteristics of the vessel and the capture system. Figure 3.1 and table 3.1 illustrate this difference between the capture rate and the CO_2 reduction with an example.

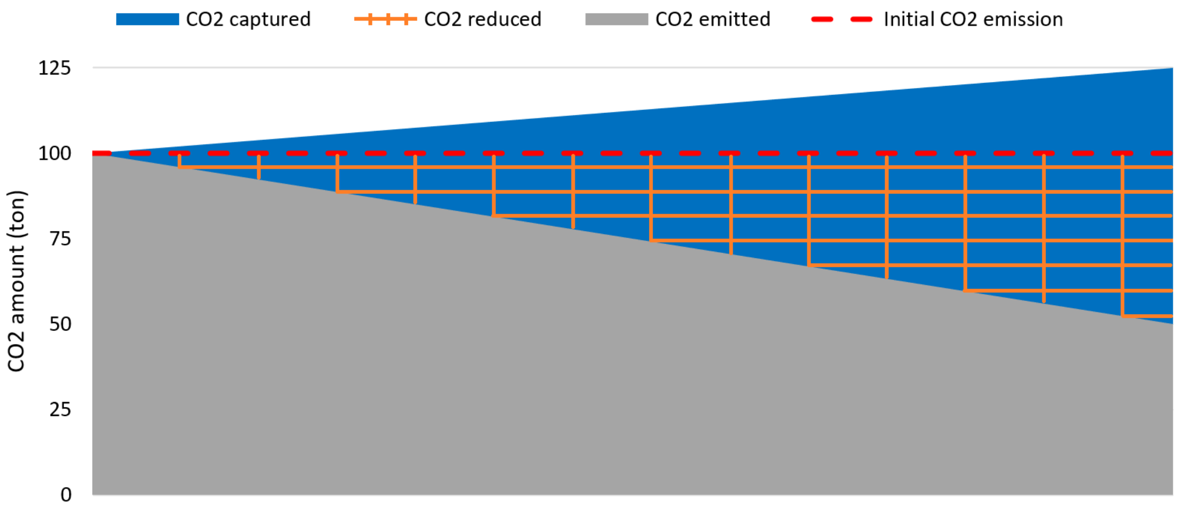

Figure 3.1: Exemplification of the difference between the captured and reduced CO_2

Table 3.1: Exemplification of the difference between the capture rate and CO_2 reduction

Initial Emissions	Net Emissions	Capt. CO_2	Red. CO_2	Capt. Rate	CO_2 Red.
100 ton	50 ton	75 ton	50 ton	**75%**	**50%**

With this maximum CO_2 emissions reduction of between 85% and 90% determined, the feasibility of reaching these reductions is studied. The first obstacle is the amount of extra carbon dioxide required to be captured due to the operation of the CC system itself. After running some examples with the developed model, the results show that, for this 85-90% CO_2 reduction, the extra amount of CO_2 required to capture is in the range of 33% and 54% of the total CO_2 captured. This means that a significant fraction of all the carbon dioxide captured does not provide the desired emissions reduction but it only compensates for the extra production of CO_2 of the CC system. This large compensation results in larger CC systems required onboard as well as a considerable increment of the CO_2 storage space to accommodate this extra carbon dioxide.

Another setback for obtaining the aforementioned high CO_2 reductions is the substantial increase in fuel consumption due to the operation of the CC system. The aforementioned examples reveal that this increase is between 46% and 100% of the fuel consumption of the base case without CC implementation. This means that the vessel would need to carry between 1.46 and 2 times more fuel to perform the same project/voyage. This, depending on the trip, could not be achieved due to the limited space for fuel storage onboard. Additionally, the economic implications of burning that amount of extra fuel could seriously affect the viability of the project/voyage.

Another aspect that could hinder achieving these high CO_2 emissions reductions is the space availability onboard the vessel to install the whole capture system and CO_2 storage. This limitation is harder to quantify than the other aspects since this space requirement strongly depends on the CO_2 production of the vessel during the whole trip. This means that, for short voyages with low engine loads, this space requirement might not suppose a limitation but for longer trips with high engine loads, the space availability can be one of the limiting factors for the CC implementation. This can be seen in the results of the following case studies.

Bearing in mind these limitations, in order to determine whether the performed case studies are deemed to be feasible, their results must accomplish the short-term objective of the IMO for CO_2 emissions reduction mentioned in the literature reviewed [13]. This objective states that the CO_2 emissions must be reduced a 20% by the year 2030.

3.2. Case studies methodology

With the maximum CO_2 reduction identified and knowing which limitations could avoid reaching this maximum reduction, the case studies are performed. The results obtained are then compared to the feasibility threshold established of, at least, a 20% CO_2 emissions reduction.

The two case studies are performed on two real ships, the *Oceanic* and the *Pioneering Spirit* both owned and operated by the company *Allseas*. The reasons behind the choice of these two vessels are mainly the difference in size between them, as can be seen in tables 3.2 and 3.5, the different operational profiles resulting from their specific duties offshore and the time spent at sea without calling at port. These differences allow testing the developed model in a wider spectrum of vessels. This will determine if it achieves the objective of determining the parameters required to study the implementation of CC regardless of the vessel's characteristics. The procedure by which these case studies are performed is as follows.

Project selection

A project that the vessel has executed is chosen. Among the projects with enough available data, the criterion for choosing the project is the maximum number of consecutive days without the ship calling at port. Knowing that the capture systems that the model outputs have a constant capture rate, this choice criterion provides the worst-case scenario in terms of onboard space requirement, especially for the storage of the CO_2. This is because, for a fixed CO_2 capture rate, a shorter project would result in less CO_2 captured.

Retrieval and cleaning of the operational profile data

The operational profiles of the ship's engines for the whole project are retrieved. Due to the nature of the vessels' operations such as Dynamic Positioning sailing or performing different tasks in a short period of time, the loading points of these engines are not constant. To reduce this fluctuation, a data cleaning process is done. The whole project timeline is segmented into conditions where an average loading point is assumed constant for each specific condition. This simplification allows the data retrieved to be used as the input for the carbon capture model.

Onboard available space

An analysis of the available space onboard the vessel to accommodate all the components of the capture system and CO_2 storage is performed. This space availability will provide some boundaries regarding the choice of the proposed design. This space availability takes into account the requirements of the different subcategories of equipment stated in section 2.6.

Data input and proposed design

The final step is running the model with the operational profile data (engine load for each condition, duration of each condition and total project time) as its input assuming the operation of the vessel with 4-stroke engines and MGO as fuel.

Based on the characteristics of the systems that the model outputs (total captured CO_2, extra fuel burnt and space requirement for all the components) and the onboard space availability identified previously, a proposed design for the capture system for each vessel is chosen. The criteria for this choice is based uniquely on the amount of CO_2 reduction that the capture system offers. This CO_2 reduction of a capture system is positively correlated with its constant CO_2 capture rate. This capture rate, in turn, is also proportional to the size of the system. Therefore, the chosen system is the largest system that fits inside the available onboard space as it is the one that provides a larger CO_2 emissions reduction.

3.3. First case study: Oceanic

The first case study was performed using the vessel *Oceanic* (figure 3.2), an offshore construction and support vessel with the characteristics stated in table 3.2.

Figure 3.2: The vessel *Oceanic* [1]

Table 3.2: Vessel *Oceanic* characteristics

Length Overall	Breadth	Operating Draught	Installed Power	Other Characteristics
129 m	25 m	8 m	6x 2.88 MW	DP2, Ice Class

3.3.1. Project selection and operational profile data

The project chosen for this case study is the removal of an offshore platform that lasted 41 days. The operational profile of one of the engines of the vessel is depicted in figure 3.3. From this operational profile, 20 conditions were identified. The duration and average engine loading of each condition are the input parameters for the carbon capture model. Figure 3.4 depicts these parameters for the same engine as figure 3.3.

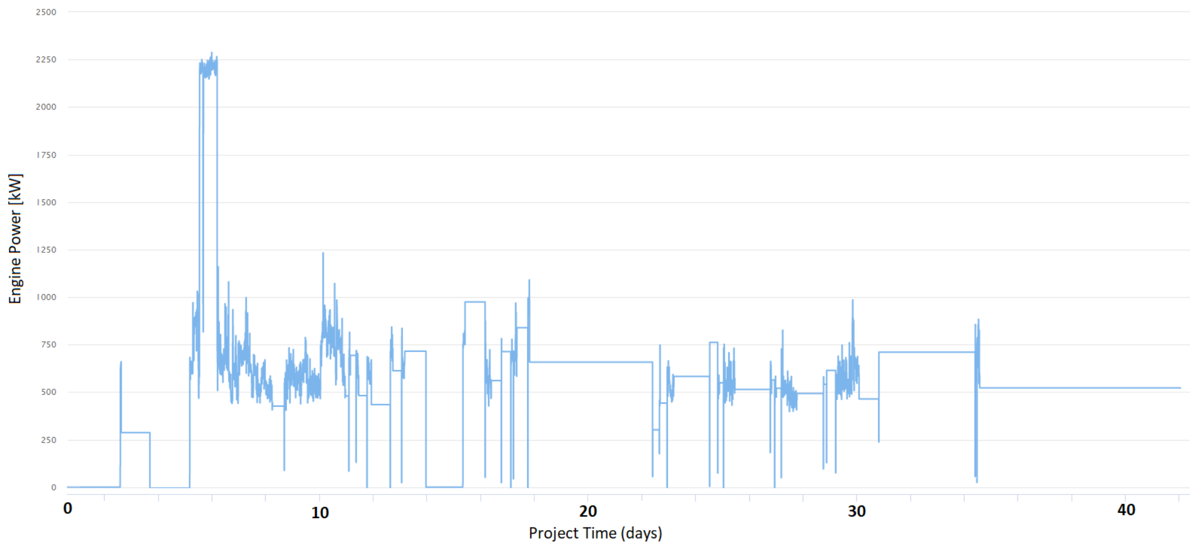

Figure 3.3: Operational profile of one the engines of the *Oceanic* during the case study [1]

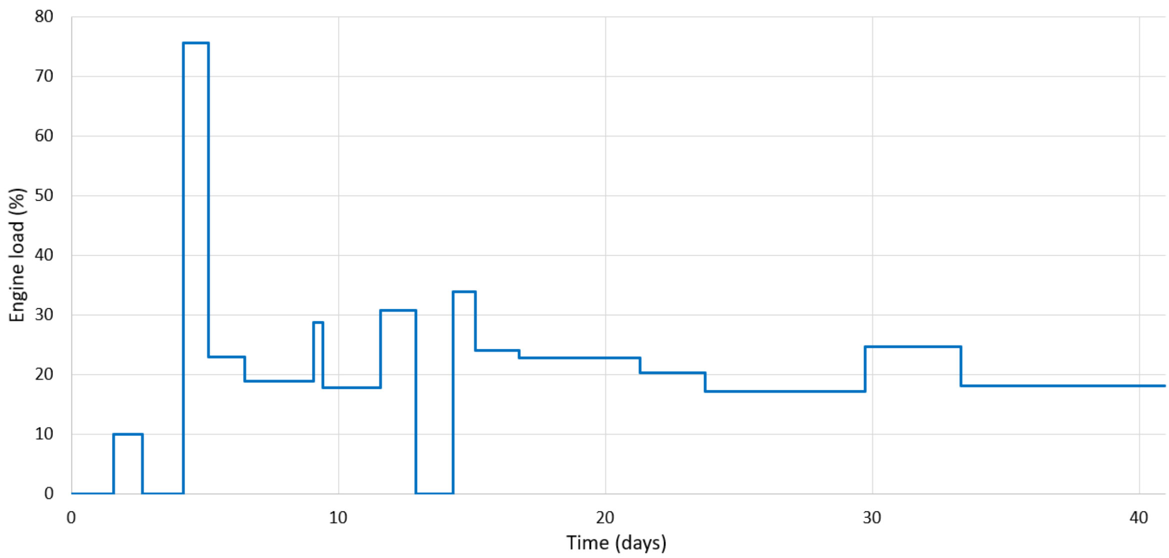

Figure 3.4: Simplification of the operational profile of one the engines of the *Oceanic* during the case study

3.3.2. Onboard space availability

After a thorough examination of the general arrangement plan of the vessel, a location for each group of elements was defined:

• **Composite boilers**: The optimal location for the boiler system is the lower part of the exhaust casing. The first reason is the fact that exhaust gases already pass through this space. Since the composite boilers require this exhaust gas to operate, this means that no major modifications in terms of relocation of the exhaust piping are required. The second reason is the amount of vertical space available in this location. This feature is convenient as it avoids placing the equipment through different decks, which could result in a large remodelling of the vessel's structure. Since the vessel is fitted with two exhaust casings, it is decided to allocate one boiler in each casing in order to increase the heat available for the capture system and the redundancy of the system.

The classification society ABS specifies in their ”Requirements for Onboard Carbon Capture and Storage” rule [76] that the exhaust piping for the carbon capture system can be combined as long as the exhaust gas from one engine flows into the other is avoided. For this specific case, is not possible to make this link before the boilers as it would produce significant pressure losses (e.g.: by the use of checks valves). For this reason, it is decided to combine the exhaust piping after the boilers and right before the blowers which can compensate for these pressure drops. This means that the exhaust lines of each engine remain separated inside the boiler.

• **Columns**: The preferred location of the column-shaped equipment is the lower part of the exhaust casing. The main reason is, again, the amount of available vertical space. In this case, the quencher, the desorber and the regenerator are located in one of the casings whereas the absorption equipment (absorber or membrane contactor) is located in the other casing.

• **Pre-capture and capture equipment**: The best location for the pre-capture and capture equipment is the engine room of the vessel. The main reason is the fact that the columns and boilers are close to the engine room. This proximity reduces the required length of the connection between the equipment.

• **Post-capture equipment**: The chosen location of the post-capture is a storage area below the main deck. The first reason for this is proximity to the CO_2 storage, which is located on the main deck. This avoids the evaporation of the CO_2 between its liquefaction and its storage. The second reason is the fact that the ABS rules for carbon capture establish that this equipment is required to be allocated in a dedicated gas-tight space, which can be easily built in the storage area without affecting significantly the operation of the vessel.

• **CO_2 storage**: The optimal location for the CO_2 storage is a dedicated area on the main deck. The reason for choosing the main deck is the fact that it allows to install the larger amount of storage space compared to any other part of the vessel. The specific location of the designated area on the main deck is close to the longitudinal centre point, symmetrically distributed with respect to the centre line. This is to reduce the detrimental effect that the CO_2 may have on the longitudinal and transverse stability of the vessel. Additionally, the selected area does not disturb excessively the normal operation of the vessel and it allows the use of the ship's cranes to load/unload the storage tanks (see next paragraph).

For the storage of the CO_2, instead of using built-in tanks onboard the vessel, a modular system of tanks is proposed. A certain number of TEU-shaped tanks are loaded on the designated area at the beginning of every project and, throughout the project, these tanks are filled with the captured CO_2. At the end of the project, these tanks are unloaded from the vessel and empty ones are loaded. This way, the amount of CO_2 storage can be adjusted to each specific project. It is determined that 21 is the maximum number of tanks that fit in the designated area. Since the project for this case study is assumed to have the maximum number of consecutive days without the ship calling at port, it is decided that these 21 tanks are the storage capacity available for this project. Figure 3.5 provides a visual representation of the designated area for the CO_2 storage (green lines).

Figure 3.5: Visual representation of the CO_2 storage area on the *Oceanic* [1]

3.3.3. Proposed design for the capture system equipment and CO_2 storage

The model is run with the input parameters assuming 4-stroke engines running on MGO and all the possible designs for the capture system are obtained. Of all of them, it is chosen the largest design that fits in the available space identified in the previous section. As mentioned at the beginning of this chapter, the reason for this choice is to obtain to maximum the CO_2 emissions reduction possible for the project. This CO_2 reduction and the increase in fuel consumption due to the CC system of the proposed design are expressed in table 3.3. Table 3.4 depicts the dimensions and occupied volume of all the elements of this proposed design.

Table 3.3: CO_2 reduction and extra fuel consumption for the proposed design for the *Oceanic*

	Vap-Comp	**Absorption**
CO2 reduction	27.5%	28%
Extra Fuel	2.3%	1.8%

Table 3.4: Dimensions and volume of all the elements of the CO_2 capture system proposed design for the *Oceanic*

Vapour-Compression Refrigeration			
Element	**Area**	**Height**	**Volume**
Boiler	5.28 m^2	5.48 m	28.92 m^3
Quencher	1.11 m^2	8 m	8.89 m^3
Absorber	2.67 m^2	8 m	21.39 m^3
Membranes	1.08 m^2	2.4 m	3.24 m^3
Desorber	0.17 m^2	6 m	1.04 m^3
Capture	2.73 m^2	1 m	2.73 m^3
Post Capture	4.88 m^2	1 m	4.88 m^3
Regenerator	-	-	-
Storage	-	-	809.54 m^3

Absorption Refrigeration			
Element	**Area**	**Height**	**Volume**
Boiler	7.21 m^2	5.87 m	36.05 m^3
Quencher	1.11 m^2	8 m	8.89 m^3
Absorber	2.67 m^2	8 m	21.39 m^3
Membranes	1.08 m^2	2.4 m	3.24 m^3
Desorber	0.17 m^2	6 m	1.04 m^3
Capture	2.73 m^2	1 m	2.73 m^3
Post Capture	3.64 m^2	1 m	3.64 m^3
Regenerator	0.06 m^2	6 m	0.34 m^3
Storage	-	-	809.54 m^3

3.4. Second case study: Pioneering Spirit

The second case study was performed using the vessel *Pioneering Spirit* (figure 3.6), a heavy-lift and pipelaying vessel with the following characteristics.

Figure 3.6: Vessel *Pioneering Spirit* [1]

Table 3.5: Vessel *Pioneering Spirit* characteristics

Length Overall	Breadth	Transit Draught	Installed Power	Other Characteristics
382 m	124 m	11 m	8x 11.2 MW	DP2, Ice Class

3.4.1. Project selection and operational profile data

The project chosen for this case study is the installation of a submarine pipe that lasted 27 days. The operational profile of one of the engines of the vessel is depicted in figure 3.7. From this operational profile, 42 conditions were identified. The duration and average engine loading of each condition are the input parameters for the carbon capture model. These parameters of the same engine are depicted in figure 3.8.

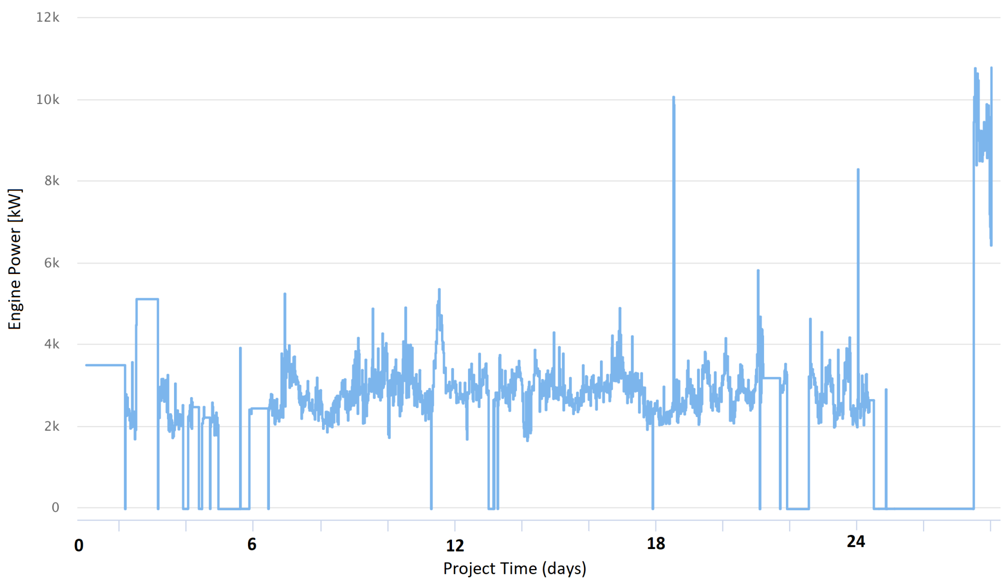

Figure 3.7: Operational profile of one the engines of the *Pioneering Spirit* during the case study [1]

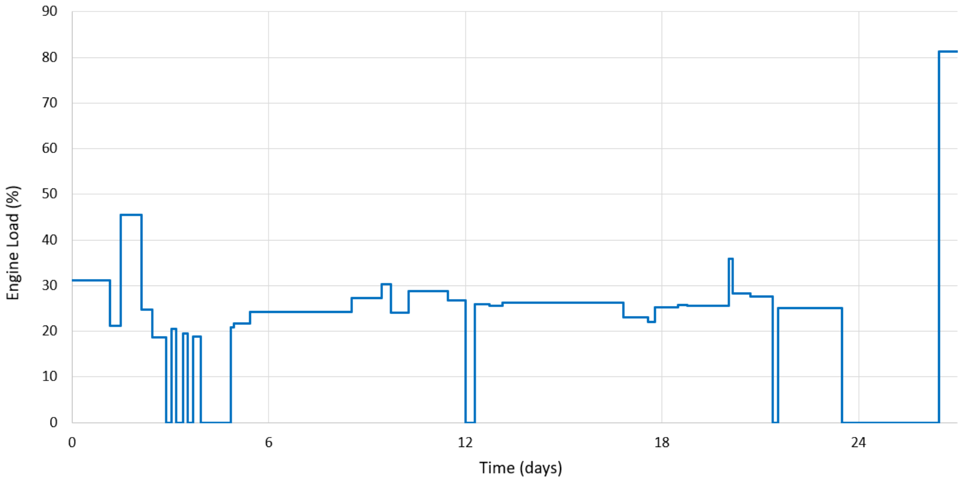

Figure 3.8: Simplification of the operational profile of one the engines of the *Pioneering Spirit* during the case study

3.4.2. Onboard space availability

After a thorough examination of the general arrangement plan of the vessel, a location for each group of elements was defined:

• **Composite boilers**: The optimal location for the boiler system is the upper part of the exhaust casing. Identically to the first case study, the main reason for opting for the exhaust casing is the fact that exhaust gases already pass through this space. Since the composite boilers require this exhaust gas to operate, this means that no major modifications in terms of relocation of the exhaust piping are required. The main reason for choosing the upper part of the casing is the fact that all the other pre-capture and capture equipment are located on the top deck of the vessel. To increase the system's redundancy, it is decided to allocate four boilers, each connected to two of the vessel's engines.

In a similar way to the first case study, the exhaust gas lines are combined after the boiler. This is to prevent the isolating elements required by regulation [76] from causing pressure drops way before the capture system's blowers.

• **Columns**: The preferred location of the column-shaped equipment is the top deck of the vessel, right next to the funnel area. The main reason is the amount of available vertical and horizontal space. For this case study, one quencher and one absorber are located on the port side of the funnel and one of each on the starboard side of the funnel. This is done to reduce and distribute better the equipment footprint. The rest of the columns, namely the desorber and regenerator are located on the aft side of the funnel.

• **Pre-capture and capture equipment**: The best location for the pre-capture and capture equipment is also the top deck, at the aft-most part. The main reason is the location of the columns and boilers also on this deck. This proximity reduces the required length of the connection between the equipment.

• **Post-capture equipment**: The chosen location of the post-capture is the main deck, in a storage area close to where the CO_2 storage is located. The first reason for this is proximity to the CO_2 storage, which is located on the main deck. This avoids the evaporation of the CO_2 between its liquefaction and its storage. The second reason is the fact that the ABS rules for carbon capture establish that this equipment is required to be allocated in a dedicated gas-tight space, which can be easily built in the storage area without affecting significantly the operation of the vessel.

In terms of the piping between the capture and post-capture equipment, most of it is in the vertical direction, going from the top to the main deck. This is a desirable situation as it means that this piping can be attached to the superstructure external bulkhead and avoid interfering with the operation of the vessel. For the horizontal pipe segments, it is decided to run them above the deck close to the starboard side of the vessel to avoid this interference as well.

• **CO_2 storage**: The optimal location for the CO_2 storage is a dedicated area on the main deck right behind the superstructure on the starboard side. The main reason for choosing the main deck is the fact that it allows the installation of a larger amount of storage space compared to any other part of the vessel. The specific designated area is chosen because it has the least detrimental effect on the regular operation of the vessel. It is also horizontally close to all the other capture equipment which means that it is not required to install a lot of piping on deck that could impact the operation of the ship. In terms of stability, since the vessel is equipped with a large arrangement of ballast tanks, it is not supposed to be a problem as it can compensate for the non-favourable location of the CO_2 storage.

Similarly to the first case study, the proposed CO_2 storage is also modular using TEU-shaped tanks instead of using built-in tanks onboard the vessel. The proposed dedicated area allows the loading and unloading of these tanks using one of the ship's cranes. For this vessel, it is determined that 50 is the maximum number of tanks that fit in the designated area. Since the project for this case study is assumed to have the maximum number of consecutive days without the ship calling at port, it is assumed that these 50 tanks are the storage capacity available for this project. Figure 3.9 provides a visual representation of the designated area for the CO_2 storage (yellow rectangle) and the capture system allocation (red square.

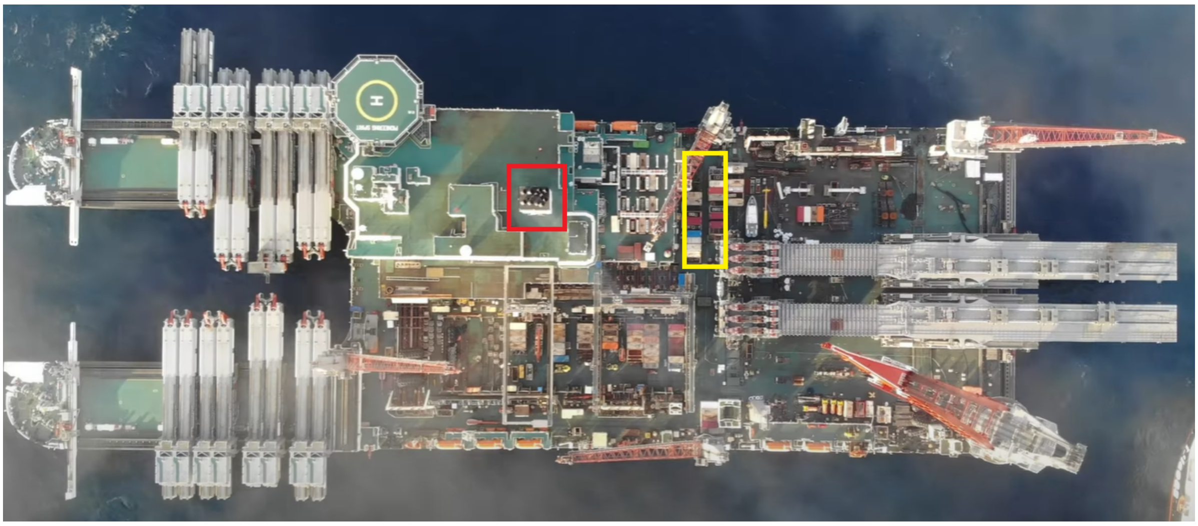

Figure 3.9: Visual representation of the CO_2 storage and the capture system area on the *Pioneering Spirit* [1]

3.4.3. Proposed design for the capture system equipment and CO_2 storage

The model is run with the input parameters (assuming 4-stroke engines running on MGO) and all the possible designs for the capture system are obtained. Of all of them, the largest design that fits in the available space identified in the previous section is chosen. As mentioned at the beginning of this chapter, the reason for this choice is to maximise the CO_2 emissions reduction possible for the project. This CO_2 reduction and the increase in fuel consumption due to the CC system of the proposed design are expressed in table 3.6.

Table 3.6: CO_2 reduction and extra fuel consumption for the proposed design for the *Pioneering Spirit*

	Vap-Comp	**Absorption**
CO2 reduction	20.55%	21.16%
Extra Fuel	1.51%	0.9%

Table 3.7 depicts the dimensions and occupied volume of all the elements of this proposed design after running the model with the input parameters and considering the space availability.

Table 3.7: Dimensions and volume of all the elements of the CO_2 capture system proposed design for the *Pioneering Spirit*

Vapour-Compression Refrigeration			
Element	**Area**	**Height**	**Volume**
Boiler	8.32 m^2	5.81 m	48.37 m^3
Quencher	1.99 m^2	8 m	15.92 m^3
Absorber	4.7 m^2	8 m	37.6 m^3
Membranes	4.05 m^2	2.4 m	9.72 m^3
Desorber	0.62 m^2	6 m	3.74 m^3
Capture	4.52 m^2	1 m	4.52 m^3
Post Capture	7.82 m^2	1 m	7.82 m^3
Regenerator	-	-	-
Storage	-	-	1927.48 m^3

Absorption Refrigeration			
Element	**Area**	**Height**	**Volume**
Boiler	9.86 m^2	6.24 m	61.51 m^3
Quencher	1.99 m^2	8 m	15.92 m^3
Absorber	4.7 $m2^2$	8 m	37.6 m^3
Membranes	4.05 m^2	2.4 m	9.72 m^3
Desorber	0.62 m^2	6 m	3.74 m^3
Capture	4.52 m^2	1 m	4.52 m^3
Post Capture	8.18 m^2	1 m	8.18 m^3
Regenerator	0.18 m^2	6 m	1.06 m^3
Storage	-	-	1927.48 m^3

3.5. Case studies conclusions

After performing these two case studies, it has been proven that the model developed is able to provide the relevant data for studying the implementation of CC onboard vessels regardless of their characteristics and operational profile. This is because the results of both case studies have been obtained without performing any modification of the model itself.

In addition to this, these case studies show that CC is a feasible method for reducing the CO_2 emissions of vessels. This is because the results of the proposed designs show a CO_2 reduction of around 28% for the *Oceanic* case study and 21% for the *Pioneering Spirit* case study which represent 600 tons and 1400 tons of CO_2 respectively. These reductions are larger than the IMO objective of CO_2 reduction of 20 %. Moreover, these emissions reductions are achieved without affecting significantly the fuel consumption of the vessel, increasing it by around 2% for the *Oceanic* and around 1.25% for the *Pioneering Spirit*. This represents 15 tons and 30 tons of extra fuel respectively.

These results, however, do not align with the ones obtained by the majority of the studies reviewed, which claim significantly higher CO_2 reductions. There are several reasons for this results difference.

The first difference is the way these studies present their results. For this study, the results are presented as CO_2 emissions reduction whereas the majority of studies in the literature present them as CO_2 capture rate. As mentioned at the beginning of this chapter, these are two different values. However, this difference does not contribute significantly to the gap between the results since the capture rates for the proposed designs are 29.8% for the *Oceanic* and 22.1% for the *Pioneering Spirit*.

The second difference is related to different values used for the CO_2 desorption heat. As mentioned in chapter 2, for the developed model, the desorption energy obtained after running the simulations with *Aspen Hysys* is around 5.1 MJ/kg of CO_2, a similar value obtained by Monteiro et al. [68] and Ros et al. [43]. However, other studies assumed a lower desorption energy, for instance, Akker [46] used 3.5 MJ/kg of CO_2 and Häggqvist [69] used 3.6 MJ/kg of CO_2. However, these values are not based on the CO_2 capture process for marine engines but for power generation plants or lean vapour compression processes. This higher desorption energy results in a higher fuel consumption in the MGO-fired boiler that reduces the overall CO_2 reduction.

Finally, the third difference is the space required for the CO_2 storage. All the papers reviewed assume a voyage duration significantly shorter than the ones used in the case studies of this thesis. These durations range from 7 hours [69] to 14 days [43], between 2.9 and 140.5 times shorter than the *Oceanic* case study and between 1.5 and 72 times shorter than the *Pioneering Spirit*. This large difference in the trip durations affects the production of CO_2 considered for the case studies. This means that if a shorter trip was assumed, a larger CO_2 reduction could be achieved since the same storage space could be filled faster with a larger capture system. For example, if the *Oceanic*'s trip duration lasted 14 days, the CO_2 reduction achieved by capturing the same amount of carbon dioxide would be 65.5%.

4 Capture Characteristics Analysis

After developing the general model for carbon capture implementation onboard vessels and testing it with the two case studies, an analysis is executed on how the type of engine, fuel and post-capture refrigeration cycle affect the performance of the CC process. This analysis is based on the first case study input i.e.: the operational profile of the vessel and the total duration of the project. This data is then run through the developed model using all the possible combinations of the aforementioned characteristics that the model offers.

The outcomes of the analysis are used to propose certain modifications to the characteristics of the case studies in order to improve the CO_2 reduction and extra fuel consumption.

4.1. Characterisitcs analysis

As mentioned, an analysis of the effect on the capture performance of the aforementioned characteristics is carried out. For this analysis, the capture process performance is defined as the ratio between the reduction of CO_2 emissions achieved and the extra fuel burnt due to the capture process.

The way this analysis is performed is by comparing the performance curves of each combination of engine type, fuel and refrigeration cycle. These curves depict the performance of each combination depending on the percentage of CO_2 reduction they achieve.

The endpoint of all of the represented curves is established at the CO_2 reduction where, in order to operate the capture system, all the exhaust gas flow produced in one of the operational conditions of the vessel is required. This goes in line with the design choice of not operating the capture system below its design point since this type of operation is not included in the model. This means that the end of the presented curves is the maximum CO_2 reduction obtainable for the designs that the developed model outputs. However, a higher CO_2 reduction could be achieved with a CC system with variable operational points

To facilitate the interpretation of the results, this analysis is split into two parts. In the first part, the different combinations that use the same fuel are compared with each other. In the second part, the combinations with the same engine type and refrigeration cycle are compared.

4.1.1. Type of engine/refrigeration cycle comparison

The first part of the analysis deals with the performance curves of the engine type/refrigeration cycle combinations for the same fuel depicted in figures from 4.1 to 4.5.

MGO Combinations

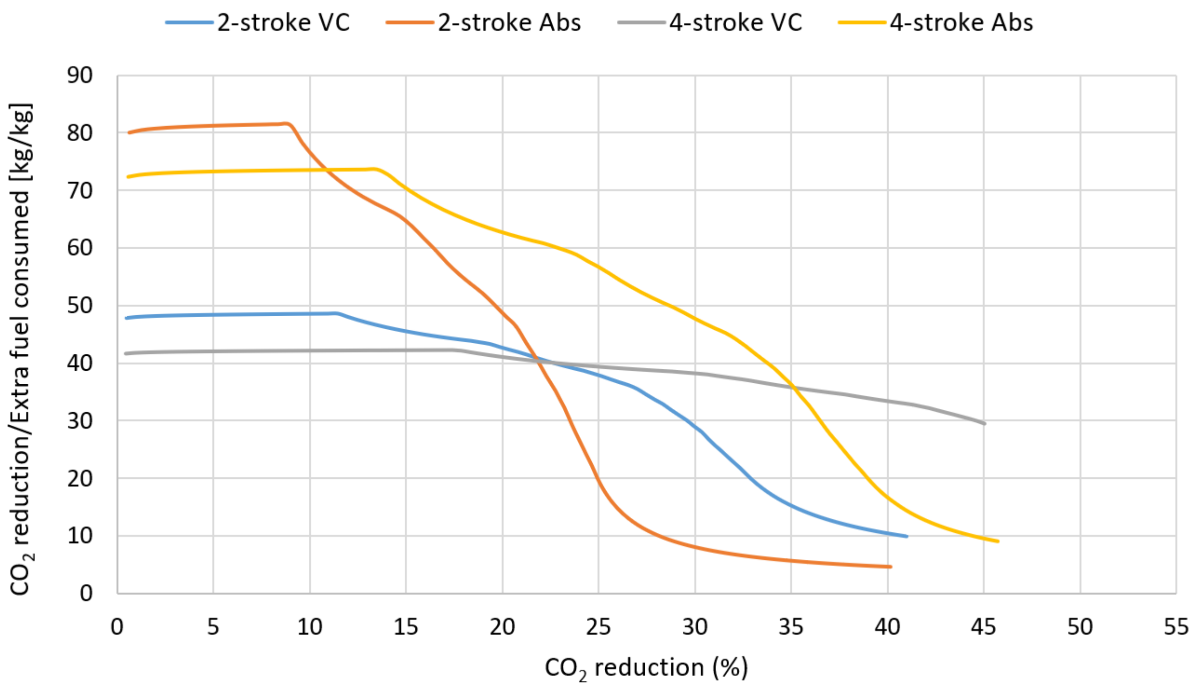

Figure 4.1: Performance curves for the MGO combinations

FO Combinations

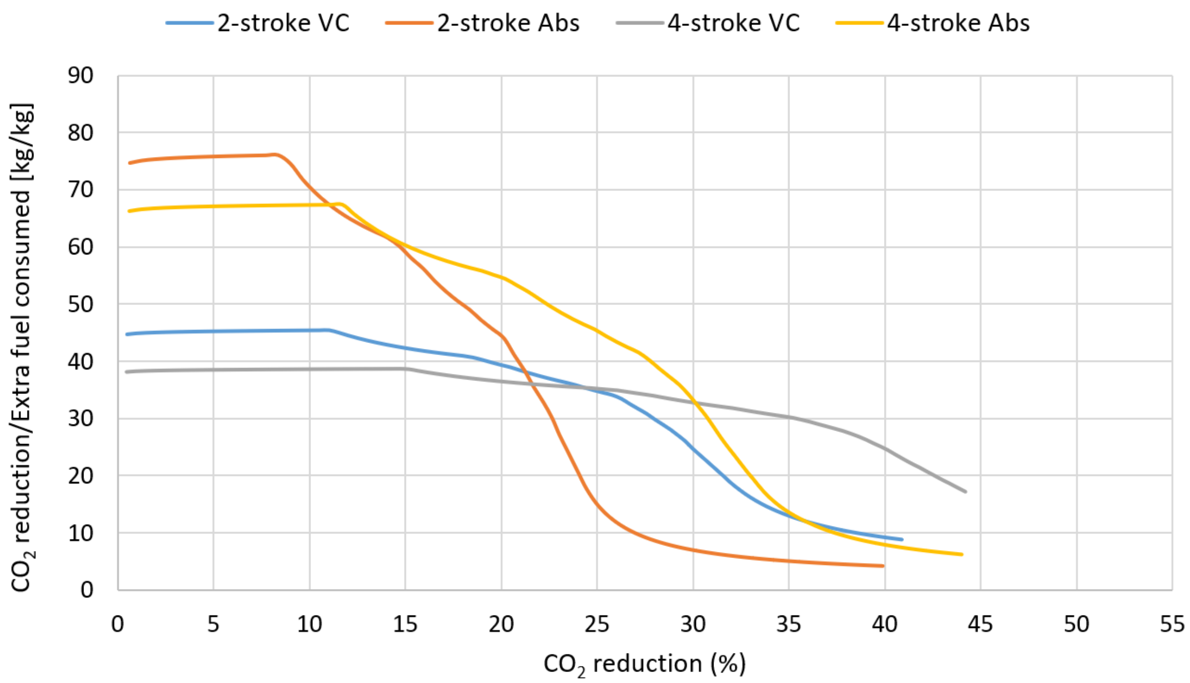

Figure 4.2: Performance curves for the FO combinations

LNG Combinations

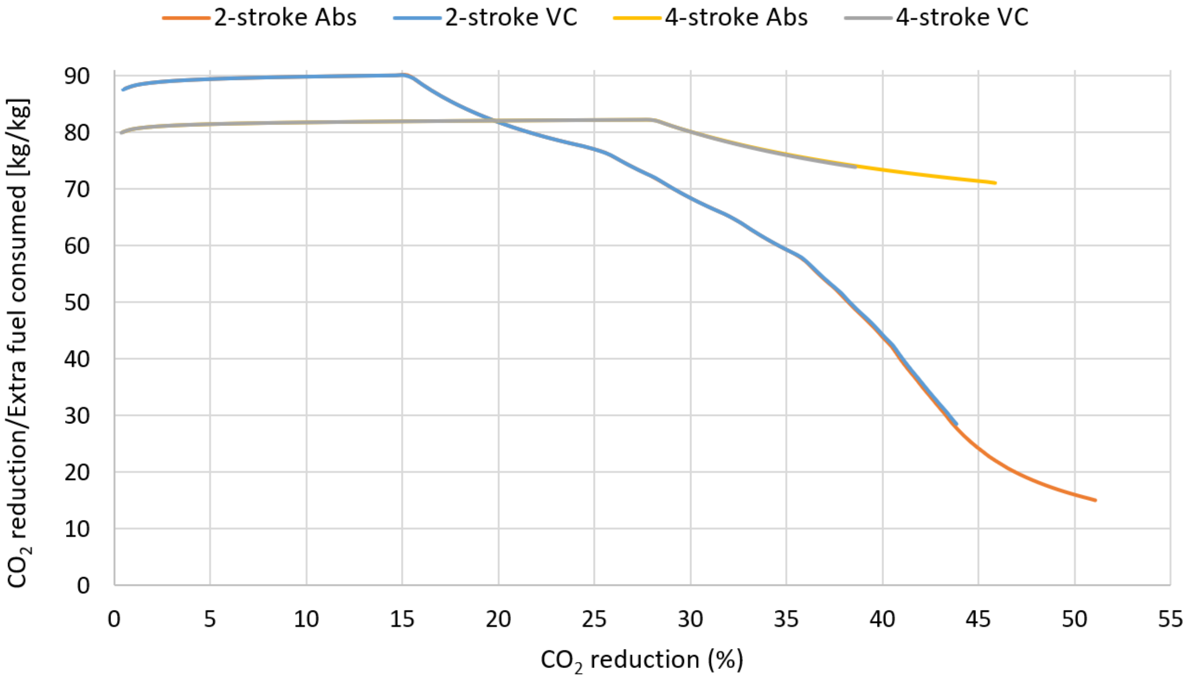

Figure 4.3: Performance curves for the LNG combinations

MeOH Combinations

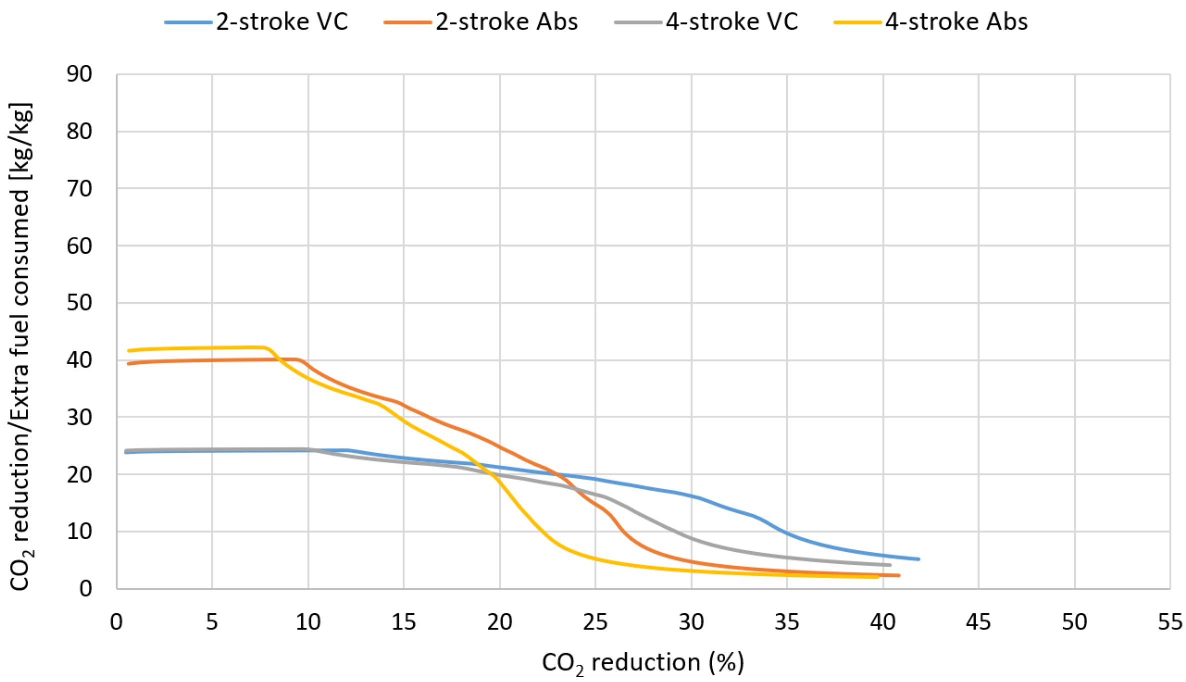

Figure 4.4: Performance curves for the MeOH combinations

B100 Combinations

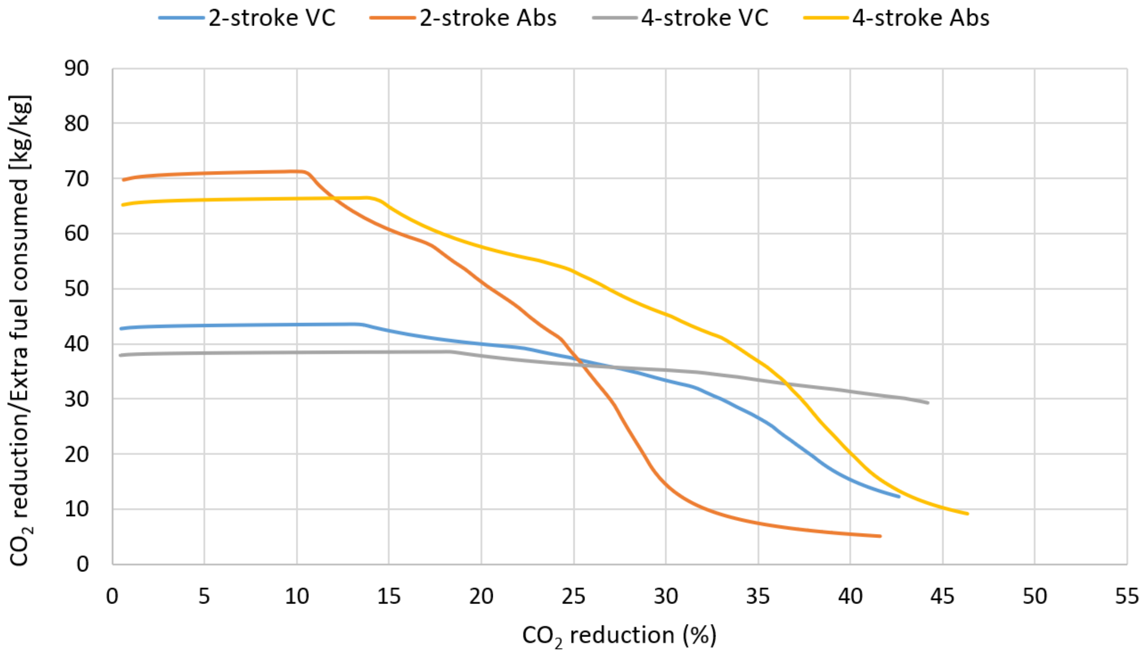

Figure 4.5: Performance curves for the B100 combinations

The first observation that can be extracted from these results is the fact that all curves follow the same shape: an initial stage where the performance is highest and nearly constant, a second stage where the performance drops and a final stage where the slope of the performance curve flattens.

The reason for this curve shape is due to extra heat produced in the MGO-fired boiler. For the initial stage, where the CC system only captures a small amount of CO_2, the exhaust gas waste heat is sufficient to operate the capture system. Therefore only a small quantity of extra fuel is used to provide the system's electric power. For the second stage, the increased size of the system requires the boiler to produce heat during some conditions. This produces the mentioned drop in performance as more fuel is needed in the boiler. For the final stage, the extra heat demand is significantly larger than the waste heat. This flattens the curve as it approaches a constant value. This constant value is the ratio between the amount of CO_2 reduced per each unit mass of extra fuel burnt in the MGO-fired boiler.

Another feature that can be observed is the length and slope of each of these segments for each combination. In all graphs, the absorption combinations have a shorter initial segment than their vapour-compression counterparts. This is because the absorption cycle requires more heat to operate therefore shortening the amount of possible CC that can operate with only the available waste heat.

The slope of the second segment also is different for each combination. The combinations with absorption refrigeration have a larger slope than the combinations with vapour-compression. This is due to the same reason mentioned previously, the absorption combinations require more heat to operate.

From the imposed highest CO_2 reduction for each combination, it can be seen that for all fuels except MeOH, the absorption cycles reach higher CO_2 reductions because more fuel is burnt in the MGO-fired boiler, creating more exhaust gas and, therefore, pushing the imposed limit further. As mentioned, this endpoint is not a physical limitation but it serves to show that the use of absorption cycles increases the amount of exhaust gas production.

For the MeOH curves (figure 4.4), the vapour-compression cycles reach slightly higher CO_2 reductions due to the higher amount of exhaust gas produced in the engines than in the MGO-fired boiler. Vapour-compression cycles need more electric power to operate, therefore more exhaust gas is produced in the engines. Since burning MeOH in the engines produces more exhaust gas than burning MGO in the boiler, the total amount of exhaust gas is higher for the vapour-compression combinations.

The LNG plot (figure 4.3) shows a significantly different behaviour than the other fuels. Both curves for the same engine type follow the same shape. The reason for this is the fact that the LNG is the main refrigerant for the CO_2 liquefaction and only a small refrigeration system is required for the bigger systems. This means that there is almost no difference in the system parameters for the same type of engine. However, the are two noticeable differences. The first one is the slope of the second segment of the curve which is higher for 2-stroke combinations due to the higher dependency of these combinations on the MGO-fired boiler. The second difference is the aforementioned maximum CO_2 reduction achieved by the absorption combinations.

In terms of which engine type has the highest performance, it depends on the CO_2 reduction that the capture system achieves. For capture systems with a lower capture capacity, 2-stroke combinations have a higher performance than the 4-stroke combinations. For example, to achieve a small CO_2 reduction of 7.5%, the performance of 2-stroke combinations is between 6.9% (B100 with absorption) and 14.9% (FO with Vap-Comp) higher. The reason for this is that smaller capture systems can operate with only the waste heat from the exhaust gas. This means that the extra fuel is only required to produce electricity for the capture system. Since 2-stroke engines have a lower specific fuel consumption than 4-stroke engines, as can be seen in figures A.2 and A.3, 2-stroke engines require less fuel to produce the same electric energy, therefore, achieving higher performances.

On the other hand, for capture systems with a high capture capacity, 4-stroke combinations have a higher performance. For instance, to achieve a CO_2 reduction of 30%, the performance of 4-stroke combinations is between 5.1% (B100 with Vap-Comp) and 83.1% (MGO with Absorption) higher. The reason for this is that large capture systems require the use of the MGO-fired boiler to operate. Since the exhaust gas from 4-stroke engines has more waste heat than the one from 2-stroke engines, less fuel is required in the MGO-fired boiler. This reduces the extra fuel required to operate the capture system, increasing its performance.

Regarding which refrigeration cycle has the highest performance, again, it depends on the CO_2 reduction that the capture system achieves. For systems with a small capture capacity, the absorption cycle combinations show a higher performance. For a 7.5% CO_2 reduction, the absorption cycle combinations have a performance of between 39.7% (2-stroke with MeOH) and 42.7% (4-stroke with MGO) higher than the vapour-compression combinations. The reason for this is that small cycles can operate with only the waste heat from the exhaust gas. This means that the extra fuel is only required to produce electricity for the capture system. Since the absorption cycle has a lower electric power requirement than the vapour-compression, the amount of extra fuel required is lower, increasing the performance of the capture system.

For capture systems with a high capture capacity, vapour-compression combinations have a higher performance. For a 40% CO_2 reduction, the performance of vapour-compression combinations is between 35.6% (4-stroke with B100) and 67.8% (4-stroke with FO) higher. The reason for this is that large capture systems require the use of the MGO-fired boiler to operate. Since the vapour-compression cycle does not require heat to operate, the fuel consumption of the MGO-fired boiler is lower than the one with absorption cycle combinations. This lower fuel consumption compensates for the higher electric power demand, making the performance of the capture system with vapour-compression cycles higher.

4.1.2. Fuels comparison

The second part of the analysis discusses the performance curves of the 5 types of fuels using the same engine type and refrigeration cycle (figures from 4.6 to 4.9).

For this second part, the extra mass of fuel is not used to determine the capture performance. The energy produced after burning this fuel is used instead. The reason is the fact that each type of fuel produces a specific amount of energy per unit mass. By using their energy, all fuels can be compared to the same benchmark. To do this mass-to-energy conversion, each amount of extra fuel is multiplied by its corresponding lower heating value expressed in table 4.1.

Table 4.1: Lower heating value of the fuels studied

MGO	FO	LNG	MeOH	B100
42.7 MJ/kg [99]	40.2 MJ/kg [99]	48 MJ/kg [99]	19.9 MJ/kg [99]	39.688 MJ/kg [100]

2-stroke and vapour-compression combinations

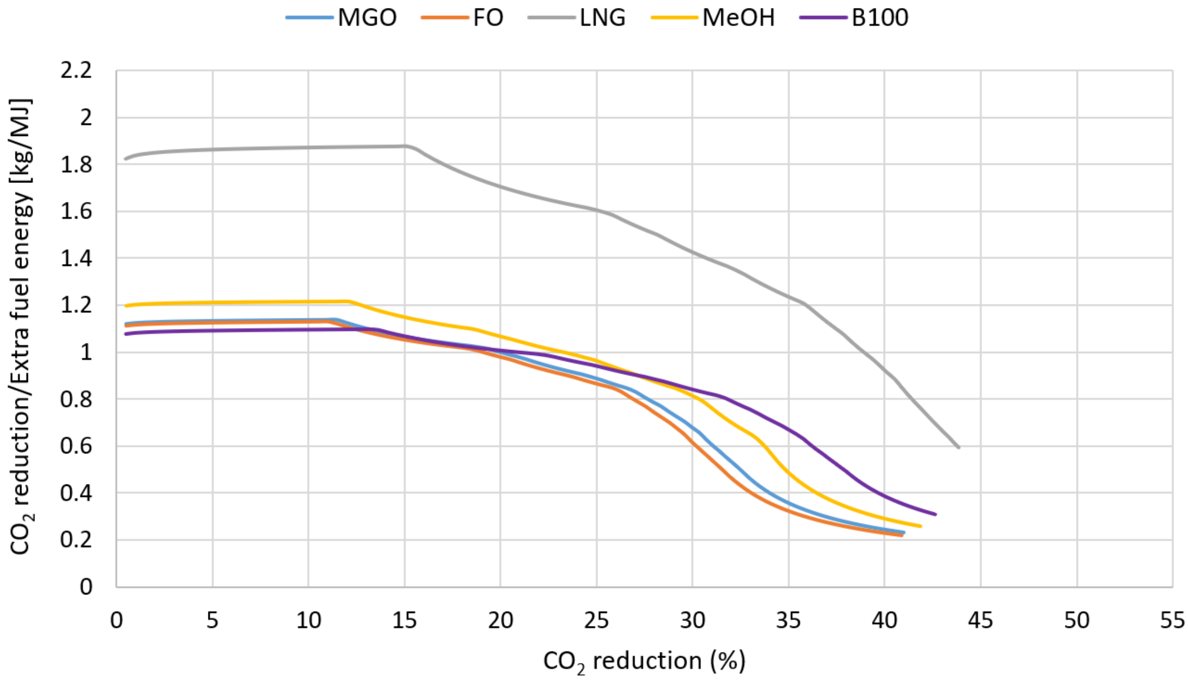

Figure 4.6: Performance curves for the 2-stroke and vapour-compression refrigeration combinations for the *Oceanic*

2-stroke and absorption combinations

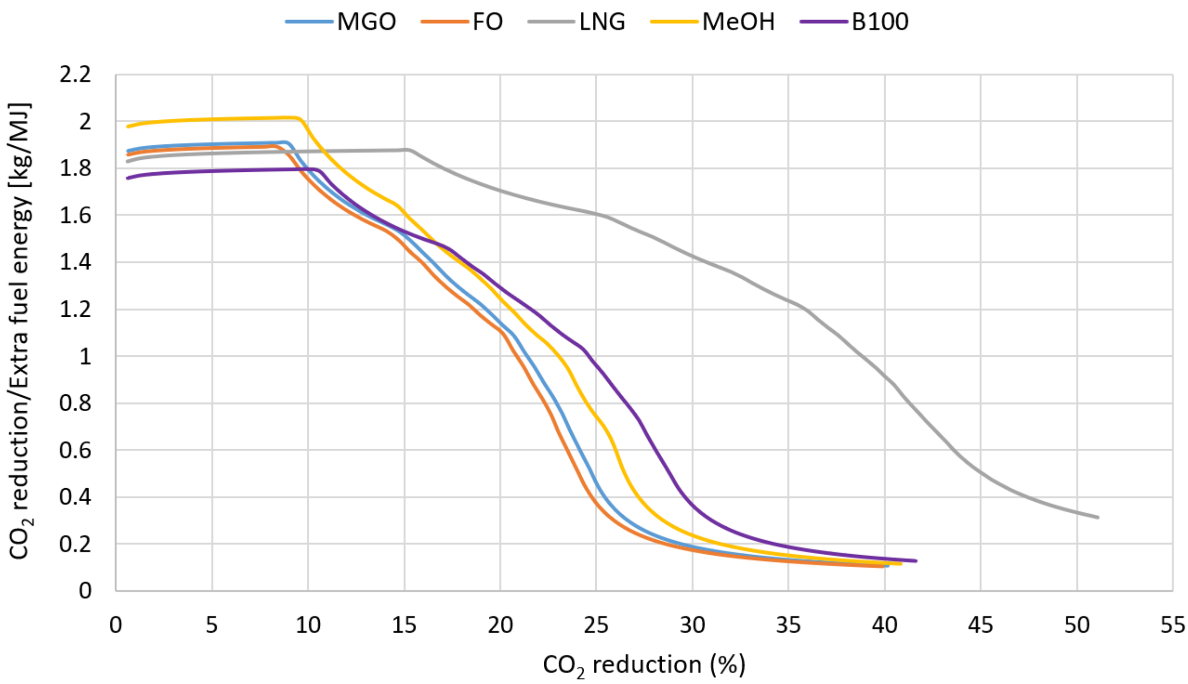

Figure 4.7: Performance curves for the 2-stroke and absorption refrigeration combinations for the *Oceanic*

4-stroke and vapour-compression combinations

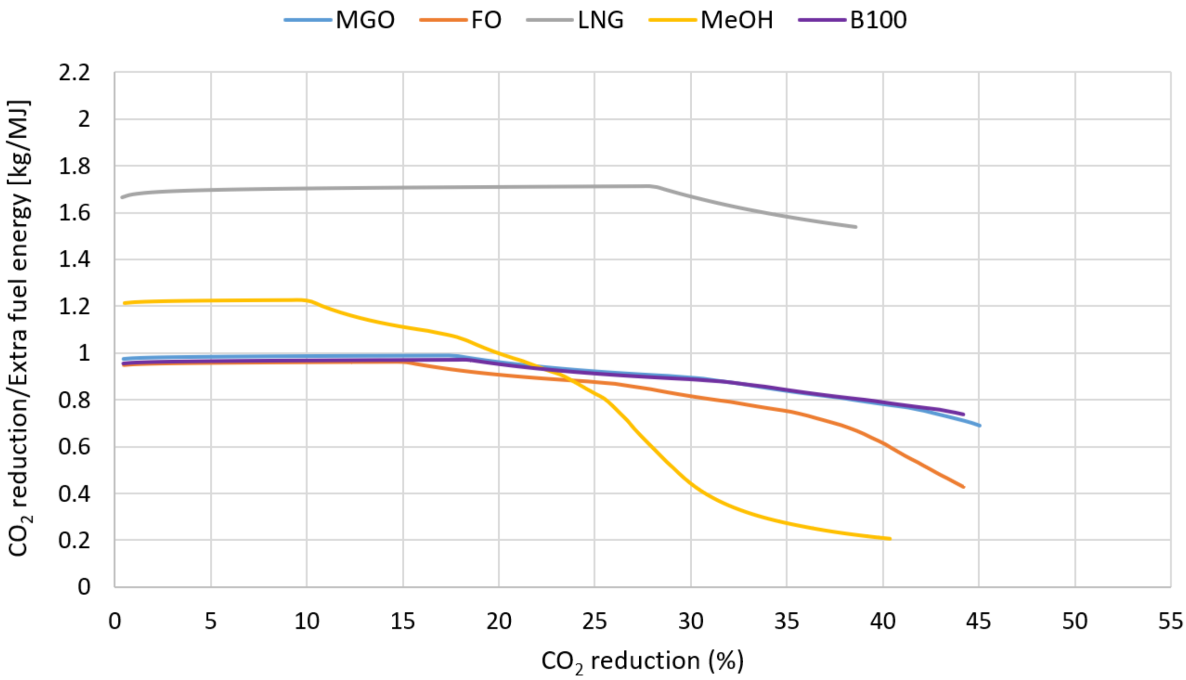

Figure 4.8: Performance curves for the 4-stroke and vapour-compression refrigeration combinations for the *Oceanic*

4-stroke and absorption combinations

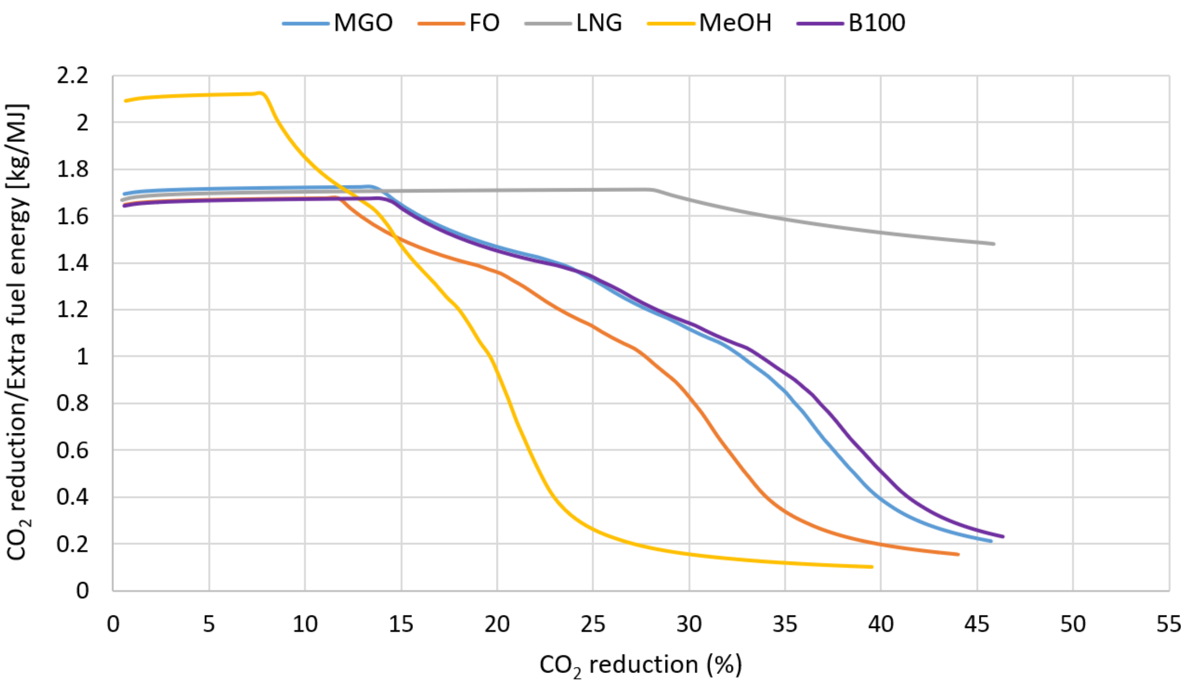

Figure 4.9: Performance curves for the 4-stroke and absorption refrigeration combinations for the *Oceanic*

Similarly to the first part of the analysis, the performance curves also show the aforementioned 3 segments. For the initial high-performance segment, it can be seen that LNG has the longest segment of all fuels for all combinations. This is due to the fact that LNG has the highest exhaust gas waste heat of all the fuels. Consequently, by using LNG, the capture system can reach larger CO_2 reductions by only using the waste heat.

On the other hand, MeOH has the shortest segment for 4-stroke combinations. This is due to lower available waste heat. This causes the need for using the MGO-fired boiler for smaller quantities of captured CO_2. For 2-stroke engines, FO and MGO have a shorter segment due to their higher CO_2 production meaning that, to achieve the same amount of CO_2 reduction, they require to capture more carbon dioxide resulting in a higher heat requirement.

Focusing on the second segment where the MGO-fired boiler heat is required, it can be seen that MeOH has the largest slope due to its lowest available waste heat which forces more fuel to be used in the MGO-fired boiler. Another interesting aspect is the fact that the MGO curve shape is more similar to the FO curve for the 2-stroke combinations and more similar to the B100 curve for the 4-stroke ones. This is due to the different engines' characteristics when MGO is used.

Focusing on which fuel combination achieves the highest performance, it can be seen that LNG outperforms the other fuels for most of the combinations. This difference in performance is up to 50%. This is because of three different factors. LNG has the lower CO_2 production of all fuels which allows higher CO_2 reductions by capturing less CO_2. Another factor is the higher exhaust temperature which increases the available exhaust waste heat per unit mass of exhaust gas. Finally, the fact that most of the CO_2 refrigeration is achieved by the LNG evaporation, reduces the overall energy requirement of the post-capture stage.

Nonetheless, MeOH offers higher performance than any other fuel for small-capacity capture systems with absorption refrigeration cycles. This performance difference is between 5% and 25%. This is because, under these conditions of no extra heat added and low electricity requirement due to the absorption cycle, MeOH combinations require less CO_2 to be captured than any other fuel in order to achieve the same level of CO_2 reduction. This decreases the electric power demand, increasing the performance of the capture process.

4.1.3. Analysis conclusions

After performing the analysis different conclusions can be extracted. The most important one is the fact that the performance of the capture process mainly depends on the heat requirement of the capture system. This can be seen in the shape of all the presented curves. In the initial segment where the exhaust gas waste heat is enough to operate the capture system, the performance peaks. When the capture system requires heat from the MGO-fired boiler, then the performance of the capture process drops significantly.

Another important aspect is the fact that the performance curves have been analysed relative to the other curves and not to the absolute performance values. This is because these absolute values would differ if other initial conditions for the analysis were used instead of the ones from the *Oceanic* case study. By performing this relative comparison, the general trends on how the characteristics affect the capture process performance have been obtained regardless of these conditions.

Focusing on the results of the analysis itself, three conclusions can be extracted. The first one is the fact that small capture systems have higher performance for 2-stroke engine combinations whereas larger capture systems show a greater performance with 4-stroke engines. This is because of the amount of available waste heat and the efficiency of the engines

With respect to the fuel, the majority of combinations and capture system sizes have a higher performance using LNG than any other fuel. The only exceptions are small capture systems with absorption refrigeration that perform better with MeOH.

Finally, regarding the refrigeration cycles, small capture systems have a higher performance with absorption cycles whereas large capture systems show a greater performance with vapour-compression. This is due to the way the heat and electricity needs change depending on the CO_2 reduction. For small capture systems, the electric requirement is the main performance driver and for large systems, the heat requirement is the driver parameter.

4.2. Case studies improvements

Using the results from the analysis of the effect of the characteristics of the vessels' engines and the capture system on the performance of the capture process, improvements to the case studies are proposed. These improvements are based on changing some of the aforementioned characteristics in order to improve the CO_2 emissions reduction compared to the base case without CC implemented as well as reduce the extra fuel required to operate the capture system. The CO_2 emissions and fuel consumption of all available combinations in the model with and without CC implementation for both case studies can be found in Appendix B it is included

4.2.1. First case study: Oceanic

For the *Oceanic* case study, the characteristics assumed are 4-stroke engines running on MGO and an absorption refrigeration cycle for the post-capture stage. These characteristics achieved a CO_2 emissions reduction of 28% and an increase in fuel consumption of 1.8% compared to the base case without CC implementation.

After examining the results from the previous analysis, the first modification proposed is to change the fuel from MGO to LNG due to its higher capture performance, as can be seen in figure 4.9. This fuel change not only improves the performance of the capture system but also reduces the overall CO_2 emissions of the project a 53% compared to the base case study without CC implementation, as depicted in figure 4.10. This reduction would represent fulfilling three-quarters of the mid-term IMO objective of reducing 70% of the CO_2 emissions [13].

In addition to this change, it is also proposed to switch the refrigeration cycle from absorption to vapour-compression. This is because both performance (figure 4.3) and overall CO_2 reduction (figure 4.10) are virtually similar for both refrigeration cycle combinations. This is due to the fact that the refrigeration cycles are significantly smaller than the other fuels' combinations since the LNG evaporation liquefies the majority of the CO_2. This, added to the fact that vapour-compression cycles require less space and elements than absorption cycles, justifies this change in the refrigeration cycle.

Finally, another modification could be implemented to reduce the overall CO_2 emissions further. This would be to change the engines of the vessel to 2-stroke engines. This modification however is not recommended for two reasons. The first one is the fact that this change would result in a capture system's performance drop of 38% (figure 4.3). The second reason is the low practicality of this change. 2-stroke marine engines' geometry and operation are significantly different than the 4-stroke engines ones, therefore, performing this change would require a whole new design for the whole power generation plant of the vessel that might not be feasible.

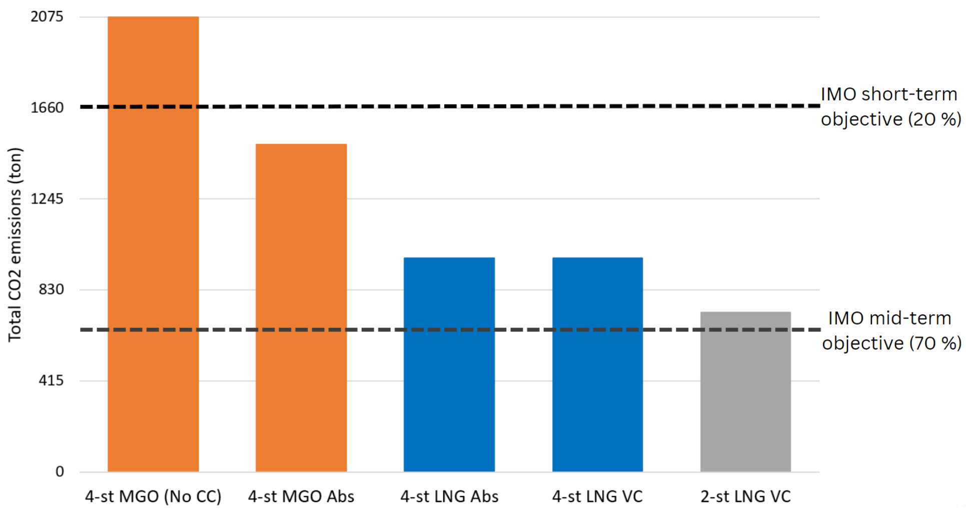

Figure 4.10: Total CO_2 emissions of the different combinations for the *Oceanic* case study

The proposed modifications would also decrease the extra fuel consumption from 1.8% to 0.1% compared to the base case without CC, as can be seen in figure 4.11. This means that the modifications would reduce the extra fuel consumption almost to the base case without CC.

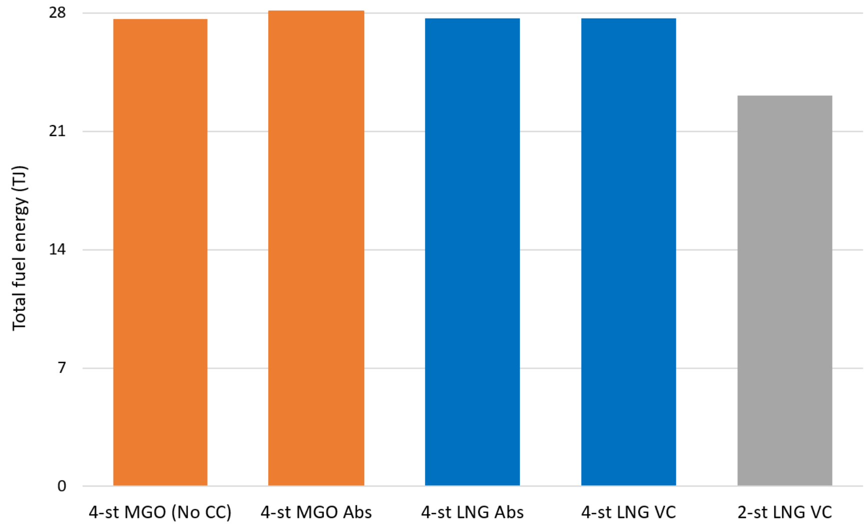

Figure 4.11: Total fuel energy of the different combinations for the *Oceanic* case study

4.2.2. Second case study: Pioneering Spirit

For the *Pioneering Spirit* case study, the characteristics assumed are the same as the ones for the *Oceanic*: 4-stroke engines running on MGO and an absorption refrigeration cycle for the post-capture stage. These characteristics achieved a CO_2 emissions reduction of 21.2% and an increase in fuel consumption of 0.9% compared to the base case without CC implementation.

The first modification proposed is the same as the one for the *Oceanic*: change the fuel from MGO to LNG. Similarly to the previous case study, this fuel change not only improves the performance of the capture system but also reduces the overall CO_2 emissions of the project a 46% compared to the base case study without CC implementation, as depicted in figure 4.10. This reduction would represent fulfilling two-thirds of the mid-term IMO objective of reducing 70% of the CO_2 emissions [13].

For this case, it is also recommended to change the refrigeration cycle to vapour-compression to reduce the capture system complexity without affecting the system's performance and the CO_2 reduction.

Finally, changing to 2-stroke engines would further reduce the CO_2 emissions a 59% but, due to the mentioned drop in performance and the impracticality of this modification, this is not recommended.

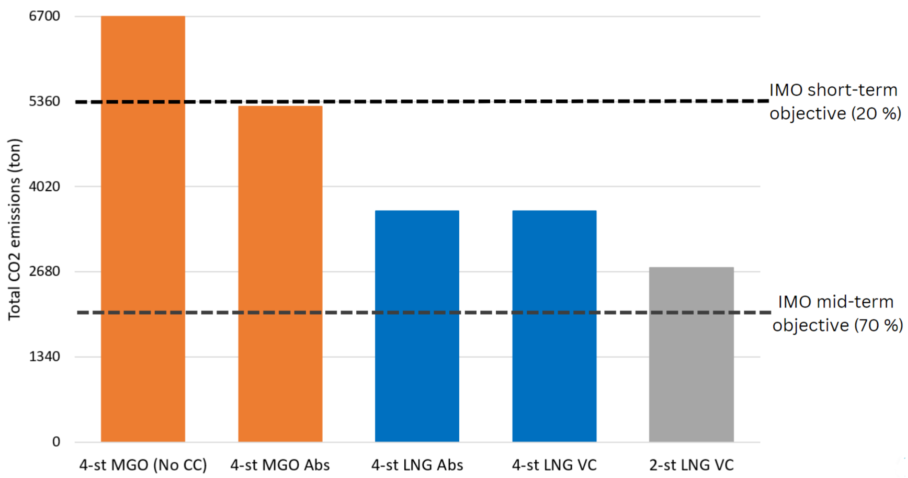

Figure 4.12: Total CO_2 emissions of the different combinations for the *Pioneering Spirit* case study

The proposed modifications would also decrease the extra fuel consumption from 0.9% to -0.5% compared to the base case without CC, as can be seen in figure 4.11. This means that the modifications would actually slightly reduce the fuel consumption of the base case without CC implementation.

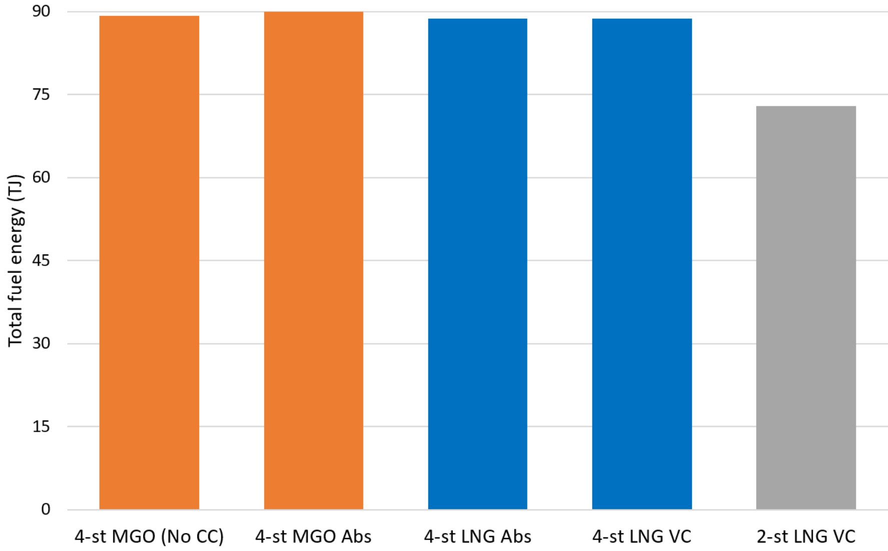

Figure 4.13: Total fuel energy of the different combinations for the *Pioneering Spirit* case study

5

Conclusions and Recommendations

During the course of this thesis, a general model for the implementation of carbon capture onboard ships has been presented, two case studies of this implementation on two different vessels have been performed as well as an analysis of how the characteristics of the vessel engines and the characteristics of the capture system affect the performance of the carbon capture process. In this chapter, the different conclusions that can be extracted from this thesis are presented. Additionally, different recommendations for future studies are also introduced.

5.1. Conclusions

The proposed objective of developing a general model for carbon capture implementation onboard vessels has been achieved. This model provides a set of carbon capture system designs for any ship based on the operational profile of the vessel and its engines' characteristics (power rating and fuel).

Two different case studies with different vessels and different operational profiles have been executed. The first case study was performed on the *Oceanic*, an offshore construction support vessel with a length of 129 m and an installed power of 17.28 MW. The second case study was performed on the *Pioneering Spirit*, a heavy-lift/pipelaying vessel with a length of 382 m and an installed power of 89.6 MW. These two case studies have been executed successfully using the developed model without any tailored modification.

The case studies confirmed that the implementation of carbon capture technology is a feasible method for reducing the CO_2 emissions onboard ships. This is because the proposed designs for the case studies achieve higher CO_2 reductions (28% for the *Oceanic* case study and 21% for the *Pioneering Spirit* case study) than the minimum reduction of 20% established by the short-term objective of the IMO by 2030 [13]. This CO_2 reduction is achieved by slightly increasing the overall fuel consumption by 1.8% and 0.9% respectively.

Moreover, these case studies proved this feasibility in worse-case scenarios than the ones proposed in the literature, strengthening the argument in favour of the suitability of the implementation of carbon capture onboard ships. This is because the periods between the CO_2 discharges assumed in the case studies are between 1.5 and 140 times larger than the ones found in the literature. This causes a larger overall production of CO_2 to be considered in the case studies, therefore, reducing the percentage of CO_2 reduction achieved by the capture system. Additionally, the heat requirement for the CO_2 desorption (5.1 MJ per kg of CO_2) used in the developed model is higher than the ones found in the literature (around 3.5 MJ per kg of CO_2). However, these literature values are not based on the CO_2 capture process for marine engines but for power generation plants or lean vapour compression processes.

Regarding the effect of the characteristics of the engines and the capture system on the capture process, different conclusions can be extracted. This effect is studied based on the performance of the capture system, defined as the ratio between the amount of CO_2 emissions reduced and the amount of extra fuel burnt due to the capture process.

The engine type, i.e.: 2-stroke or 4-stroke engines, affects the behaviour of the capture process. Smaller capture systems have performance between 6.9% and 14.9% (for a CO_2 reduction of 7.5%) higher when implemented with 2-stroke engines compared to 4-stroke engines. On the other hand, for larger capture systems, 4-stroke engines reach better results with a performance difference of between 5.1% and 83.1% (for a CO_2 reduction of 30%). The main reason behind this is the available exhaust waste heat of each engine type. For 2-stroke engines, this heat is lower, meaning that only small systems can operate with this limited heat whereas 4-stroke engines allow bigger capture systems to operate more effectively due to their higher waste thermal energy availability.

Regarding the fuel type, the analysis shows that, in general, LNG has a performance up to 50% higher than any other fuel when used in conjunction with a carbon capture system. The main reason for this is the combination of the fact that the refrigeration of the CO_2 is achieved using the evaporation of the LNG with its low CO_2 production and high waste heat availability. Nonetheless, other fuels also achieve the highest performances when used with specific combinations of engine types and refrigeration cycles. This is the case for small capture systems that use absorption refrigeration for the CO_2 liquefaction for which MeOH has a performance between 5% and 25% higher than all the other fuels.

The last characteristic analysed is the chosen refrigeration cycle for the CO_2 liquefaction. In general, absorption cycles display a performance of around 41% higher for smaller systems (for a CO_2 reduction of 7.5%) whereas vapour-compression cycles performance is between 35% and 65% higher for larger systems (for a CO_2 reduction of 40%). The reason behind this is the amount of electricity and heat that these systems require. For small systems, the exhaust waste heat is enough to operate the absorption cycle and, since this cycle has a lower electricity demand, it is more effective. For large systems that require a significant amount of fuel for the MGO-fired boiler, the vapour-compression cycle is a better choice as its higher electricity demand is compensated by not requiring thermal energy to operate.

Using the outcomes from the analysis, improvements to the case studies are proposed. Apart from installing the proposed capture systems, if the fuel is switched from MGO to LNG, larger CO_2 reductions can be obtained. These reductions change from 28% to 53% for the *Oceanic* case study and from 21% to 46% for the *Pioneering Spirit* case study. This represents fulfilling 75% and 66% respectively of the IMO's mid-term objective of reducing 70% the CO_2 emissions by 2040 [13].

Additionally, this fuel modification also decreases the extra fuel consumption from 1.8% to 0.1% for the *Oceanic* case study meaning that there is barely any extra fuel consumption compared to the base case without carbon capture implementation. For the *Pioneering Spirit* case study, the extra fuel consumption decreases from 0.9% to -0.5% meaning that there is even a slight reduction in the fuel requirement compared to the base case without carbon capture implementation.

5.2. Recommendations

Different recommendations for future research are presented. These recommendations are based on the inclusion of aspects that have not been considered in this thesis. In addition to this, the implementation of carbon capture onboard ships can also be studied by focusing on different scopes.

The first aspect is the study of how capture systems behave when they operate in off-design conditions. This would allow an optimisation of the operational point of the capture system depending on the vessel's conditions which could result in an increase in the capture system's efficiency and the overall CO_2 emissions reduction.

Another aspect worth considering is the study of various projects in conjunction instead of just one. This would shed light on how the performance of the capture process onboard ships changes depending on a wider range of the vessel's operational profiles.

The effect on the ship's operability could also be studied. For example, how the stability is affected after installing a carbon capture system or how much cargo/working space is lost because of that.

Another feature not considered in this thesis is the actual operation and maintenance of the capture system itself. Studying these two topics could also provide insights regarding the size of the capture system or the choice of the refrigeration cycle for the CO_2 liquefaction. This is because, for example, a certain capture system size could be preferred because of its higher CO_2 emissions reduction but, in practice, its operation and maintenance program could interfere excessively with the normal operation of the vessel.

Regarding the scopes, this thesis focused only on the technical part of the implementation of carbon capture onboard ships. There are many other scopes in which this topic can be approached. The first one would be the economic side of this implementation e.g.: Studying the most economically optimal design for a capture system onboard or studying the economic cost of using carbon capture compared to other CO_2 emissions reduction technologies.

The second scope could be related to proposing the infrastructure, logistic chain and policies required to attract shipowners and shipbuilders to include carbon capture systems onboard their new/already built vessels. These proposals could be related to more restrictive policies against CO_2 emissions or implementing a network of CO_2 transport where it could be transported easily to its final destination.

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A

Appendix: System Modelling

A.1. Iterative process

As mentioned at the beginning of chapter 2, the general model consists of the mathematical model of a capture system embedded in an iterative process. This iterative process is required since the initial loading conditions of the engines that correspond to the input operational profile will be modified. This is because the power requirement of the capture system increases these initial loading conditions of the engines. This means that the capture system model needs to determine all the parameters again with the updated loading conditions. The way this iterative process works is depicted in figure A.1.

The iteration model avoids transferring the capture system load to engines that do not produce energy, such as main engines dedicated uniquely to the vessel´s propulsion. Additionally, it also does not transfer this load to not running. This is because it is not realistic to start an engine just to take in the power requirement of the capture system due to the high inefficiency of doing so.

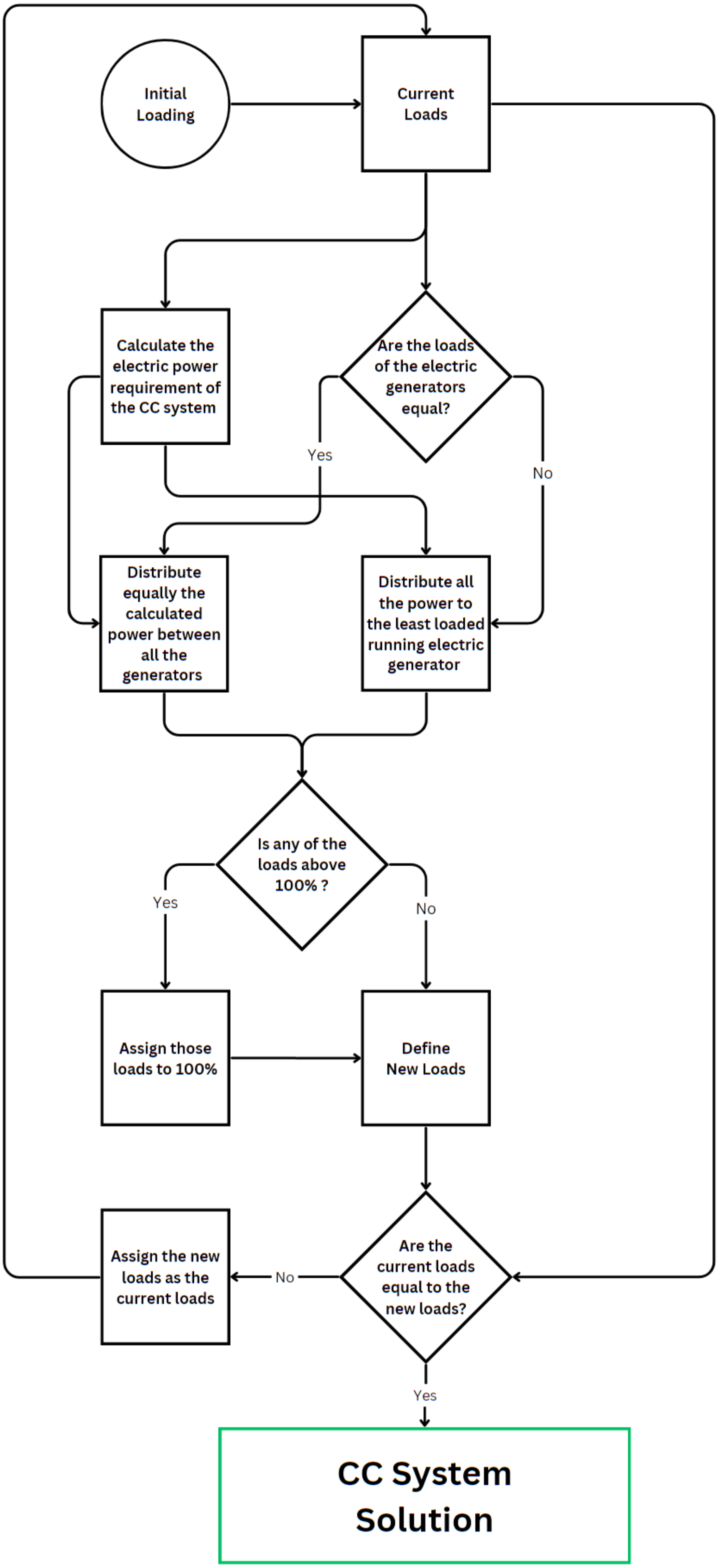

Figure A.1: Flowchart of the iterative process included in the general model for CC implementation board ships

A.2. Engine parameters modelling

A.2.1. Specific Fuel Consumption

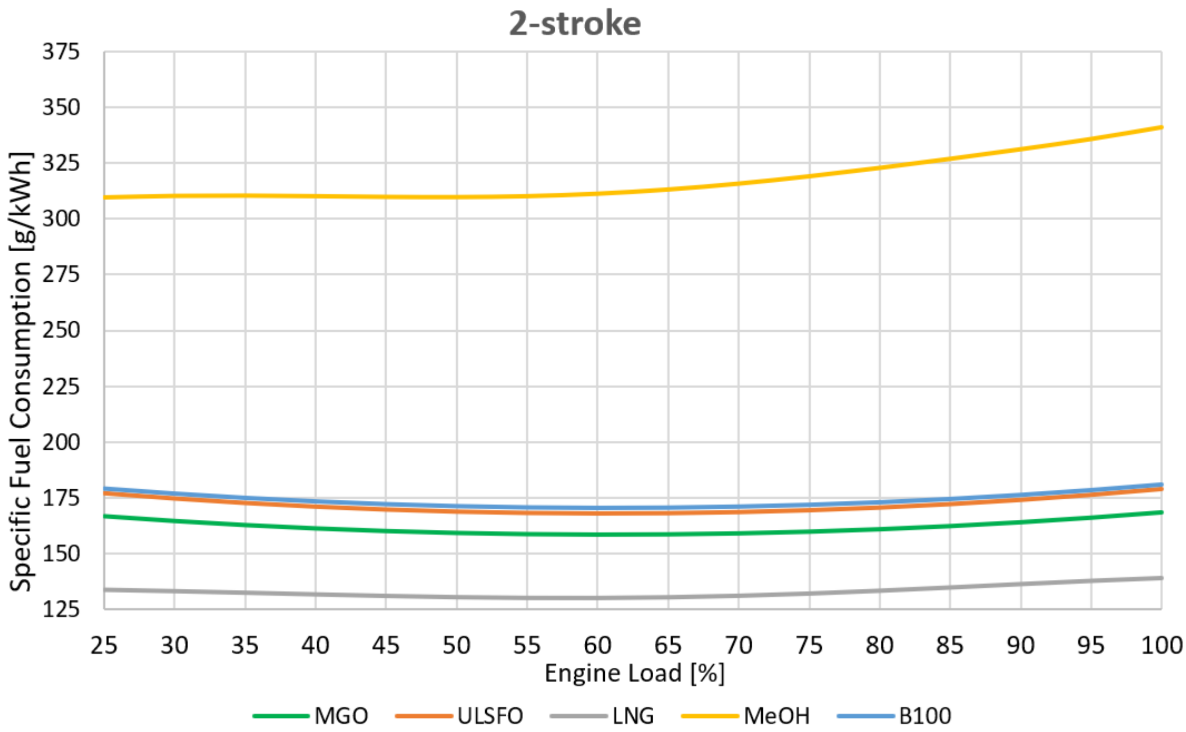

Figure A.2: SFC vs engine load for 2-stroke engines

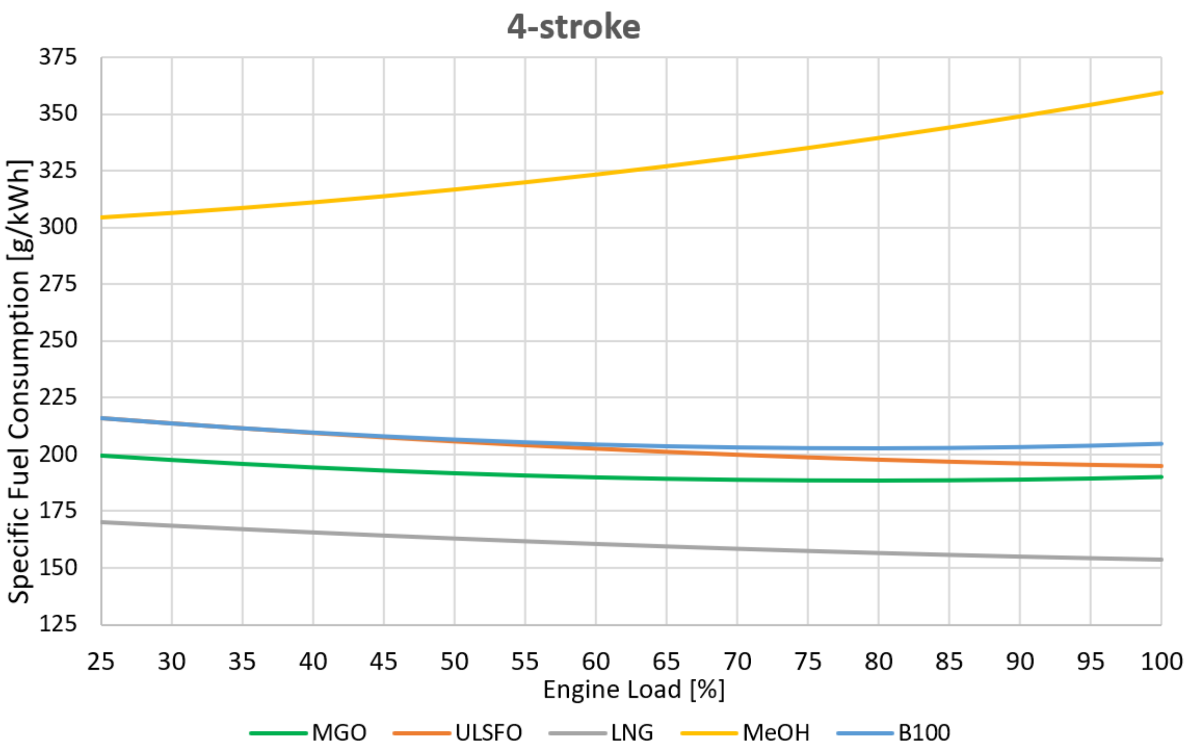

Figure A.3: SFC vs engine load for 4-stroke engines

A.2.2. Exhaust gas CO_2 concentration

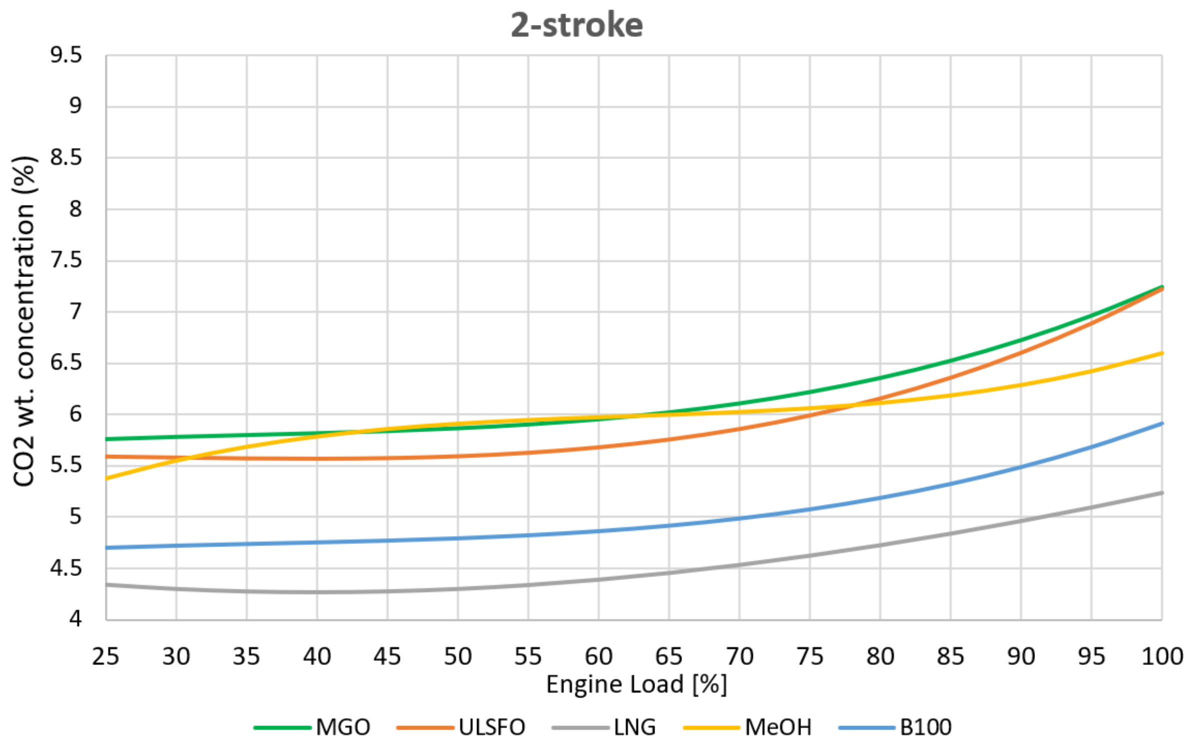

Figure A.4: Exhaust gas CO_2 concentration vs engine load for 2-stroke engines

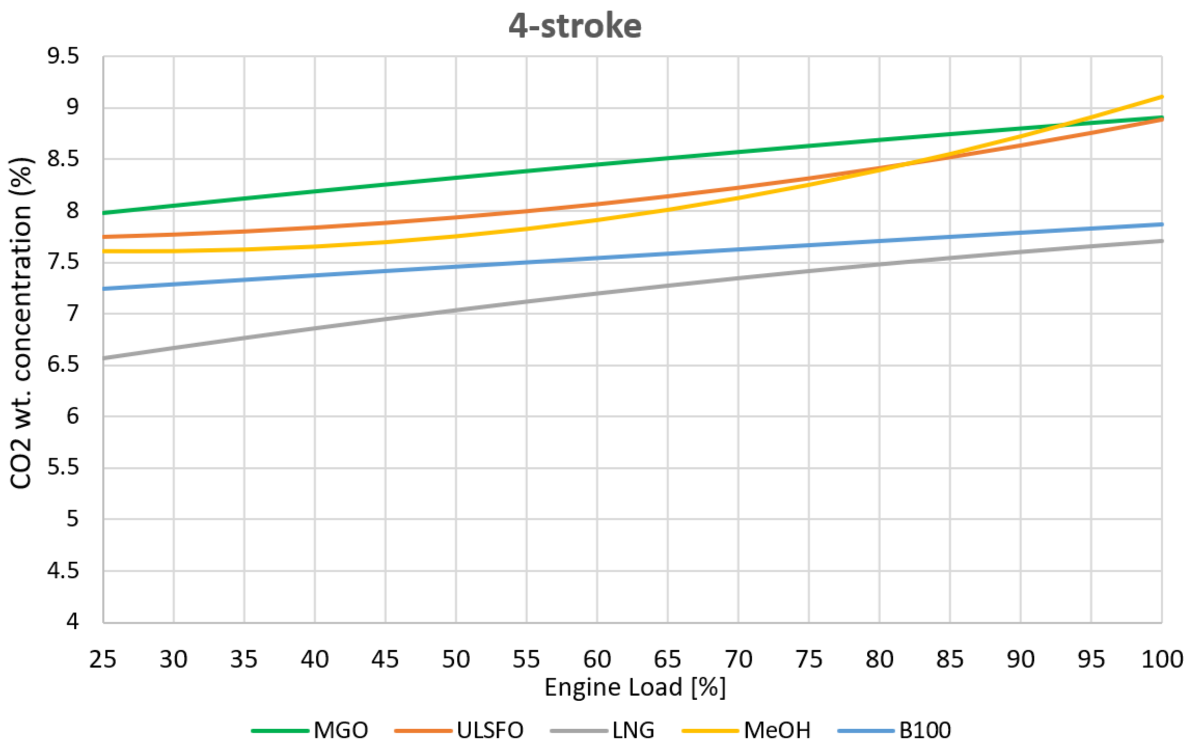

Figure A.5: Exhaust gas CO_2 concentration vs engine load for 4-stroke engines

A.2.3. Exhaust gas temperature

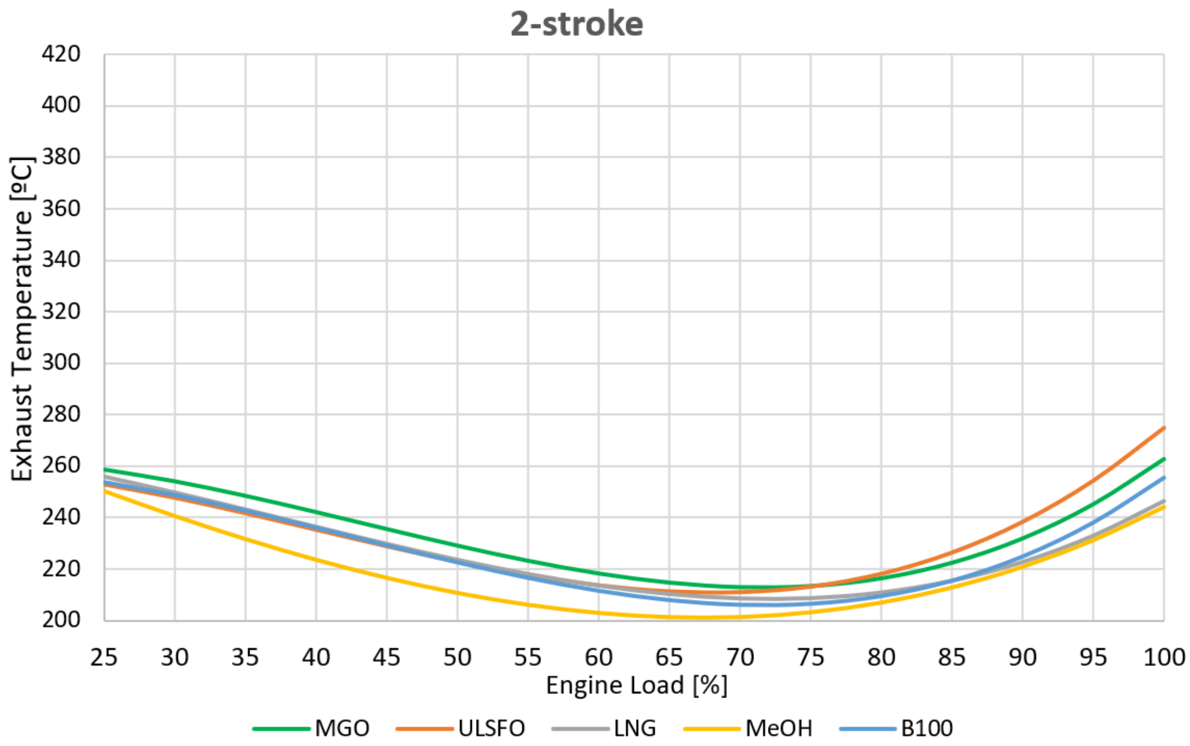

Figure A.6: Exhaust gas temperature vs engine load for 2-stroke engines

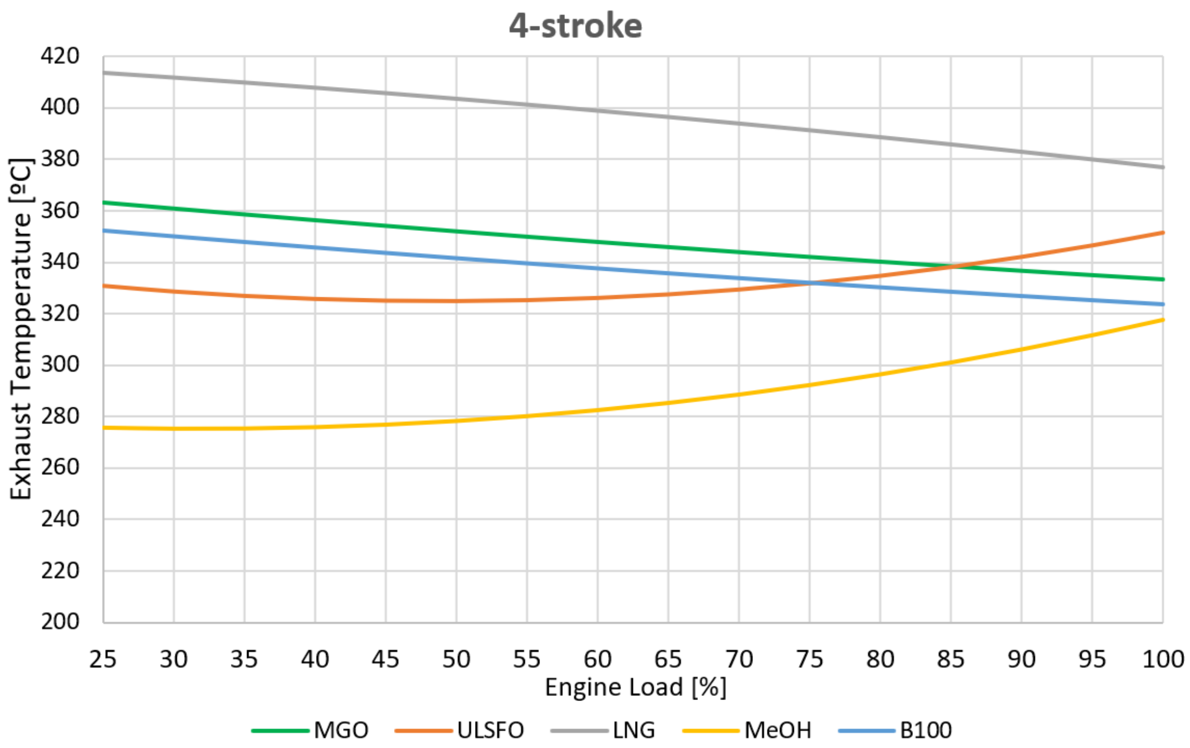

Figure A.7: Exhaust gas temperature vs engine load for 4-stroke engines

A.3. Aspen Hysys simulations

To check that the capture part of the general model results are accurate and to obtain certain required values for the general model, like the heat required to capture 1 kg of CO_2 or the efficiency of the absorber column, different using *Aspen Hysys* simulations were performed. Figure A.8 shows all the components of the capture stage modelled in *Aspen Hysys* and table A.1 depicts the inputs and outputs of all the simulations performed. The two values at the bottom of the table are the used values in the general model and correspond to the average of all the values obtained in all the simulations.

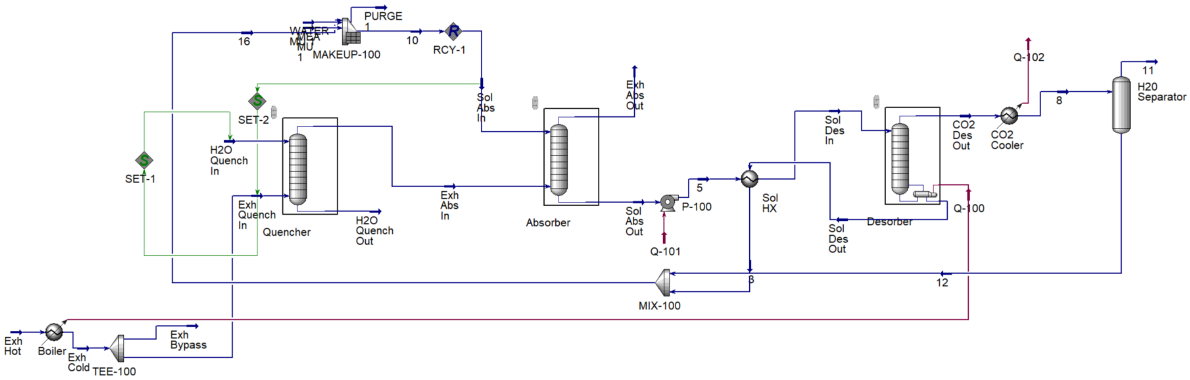

Figure A.8: Capture stage modelled using *Aspen Hysys*

These simulations use a constant value of exhaust gas of 20 kg/s and a constant CO_2 concentration of 7.6%. The reason behind choosing this concentration is the fact that it is around the CO_2 average concentration of the exhaust gas generated in the 4-stroke engines (figure A.5).

The variable that changed in each simulation was the exhaust temperature. The range of temperature goes from 200ºC to 350ºC. This range is chosen as it represents the mid-lower range of the modelled exhaust temperatures which could be considered as well as a worst-case scenario since they are the ones with less available thermal energy for the capture system.

Table A.1: *Aspen Hysys* simulation values

Sim.	m_{exh} [kg/s]	m_{CO_2} [kg/s]	T_{exh} [ºC]	Q_{av} [kW]	$m_{exh\ CC}$ [kg/s]	m_{CO_2CC} [kg/s]	m_{sol} [kg/s]	m_{CO_2Capt} [kg/s]	Abs. Eff [%]	h_{abs} [MJ/kg]
1	20	1.518	200	754.2	2.2	0.167	2.86	0.157	94.115	4.919
2	20	1.518	215	1079	3	0.228	3.9	0.219	96.205	5.049
3	20	1.518	230	1405	4	0.304	5.2	0.285	93.884	5.053
4	20	1.518	245	1734	4.9	0.372	6.37	0.351	94.342	5.076
5	20	1.518	260	2061	5.8	0.440	7.54	0.414	93.992	5.106
6	20	1.518	275	2391	6.7	0.509	8.71	0.477	93.829	5.137
7	20	1.518	290	2722	7.6	0.577	9.88	0.539	93.484	5.174
8	20	1.518	305	3054	8.6	0.653	11.18	0.601	92.058	5.180
9	20	1.518	320	3388	9.5	0.721	12.35	0.662	91.797	5.195
10	20	1.518	335	3723	10.5	0.797	13.65	0.720	90.399	5.233
11	20	1.518	350	4059	11.3	0.858	14.69	0.782	91.163	5.257
									93.206	5.125

A.4. Space requirement modelling

A.4.1. Columns space

For the modelling of the space requirement for the columns, it was assumed a packing structure height of 6 meters with an extra meter above and below the column, adding up to 8 meters. The diameter of the column is the design variable that allows the change in size. Using *Aspen Hysys*, a correlation between the amount of fluid passing through the column and the optimal diameter of the column was obtained. Additionally, the columns are not modelled as cylinders but as rectangular prisms with a length and width equal to the calculated diameter and a height equal to 8 meters. This over dimensioning allows to take into account piping and another elements that are required for the operation of the columns.

Table A.2 indicates the fluid used to model each column and the mathematical function obtained.

Table A.2: Mathematical functions for the columns space modelling

Component	Fluid (x) [kg/s]	Space required (y) [m^3]
Quencher	CC Exh gas	y = 3.6288·x + 0.2918
Absorber	MEA Solvent	y = 6.4283·x + 1.5958
Desorber	MEA Solvent	y = 0.3319·x + 0.0194
Regenerator	NH_3-H_2O mix	y = 1.0406·x + 0.0624

A.4.2. Heat exchangers

For the modelling of the space requirement for the heat exchangers, the *Aspen Exchanger Desing and Rating* tool was used. This tool provides the most feasible design parameters of the heat exchanger for the input conditions of the two fluids. All the heat exchangers in the model are assumed to be shell-and-tube type. Among these design parameters, the length and diameter of the shell are provided. After obtaining the volume parameters of the designs for different mass flow rates, a mathematical function was obtained using curve fitting. Like the column modelling, the heat exchangers are not modelled as cylinders but as rectangular prisms.

Table A.3 indicates the fluid used to model each heat exchanger and the mathematical function obtained. It has to be pointed out that although two fluids pass through these heat exchangers, only one of them is used in the dimensioning equation. This is because, with the flow rate known of one of the fluids, the other flow rate is also known as both of them hold a proportional relationship. This makes unnecessary the size modelling using both fluids' flow rates.

Table A.3: Mathematical functions for the heat exchangers space modelling

Component	Fluid (x) [kg/s]	Space required (y) [m^3]
Rich-Lean MEA HX	MEA Solvent	$y = 0.1825 \cdot x^{0.7162}$
CO_2 post-desorption cooler	CC CO_2	$y = 1.2413 \cdot x^{0.8152}$
CO_2 compression coolers	Cooling H_2O	$y = 0.1959 \cdot x^{0.7227}$
LNG-CO_2 HX	LNG	y = 10.74·x + 0.0924
NH_3 evaporator	NH_3	$y = 1.124 \cdot x^{0.8409}$
NH_3 compression cooler	Cooling H_2O	y = 0.4372·x + 0.0848
NH_3 condenser	Cooling H_2O	y = 0.0236·x + 0.0335
NH_3/H_2O mix cooler	NH_3-H_2O mix	$y = 2.3335 \cdot x^{0.9134}$
NH_3/H_2O mix-H_2O HX	NH_3-H_2O mix	$y = 0.3445 \cdot x^{0.8716}$

A.4.3. Remaining components

For the modelling of the space requirement for all the remaining components, the data of different manufacturers was used to obtain the mathematical functions. Similarly to the columns, the space of each component is assumed as prisms. The data required for each component was obtained using the technical sheet of the following models:

- **Composite boiler:** Composite boiler model *OC-TCi* from the company *Alfa Laval Aalborg*
- **Blower:** Axial flow blower model *MPV A1K* from the company *Nyborg-Mawent*
- **Pumps:** Centrifugal pumps models *ESL* and *NSL* from the company *DESMI*
- **Compressors:** CO_2 and NH_3 compressors models *HK* and *J* from the company *MYCOm*
- **Fresh water generator:** Reverse osmosis fresh water generators from the company *Wärtsilä*

Table A.4 indicates the fluid used to model each component and the mathematical function obtained.

Table A.4: Mathematical functions for the components space modelling

Component	Fluid (x) [kg/s]	Space required (y) [m^3]
Composite Boiler	Waste Heat Steam	$y = 36.758 \cdot x + 0.2918$
Blower	CC Exh gas	$y = 5.3e\text{-}4 \cdot x^2 + 3.13e\text{-}2 \cdot x + 7.28e\text{-}4$
Pumps	H_2O / MEA	$y = 0.057173 \cdot x^{0.3739}$
Compressors	CC CO_2 / NH_3	$y = 1.3881 \cdot x^{0.1753}$
Fresh water generator	Quencher H_2O	$y = 0.92625$ [1]

[1] The size of the fresh water generator is constant as the manufacturer provides the same size for a different range of models.

B

Appendix: Case studies combinations

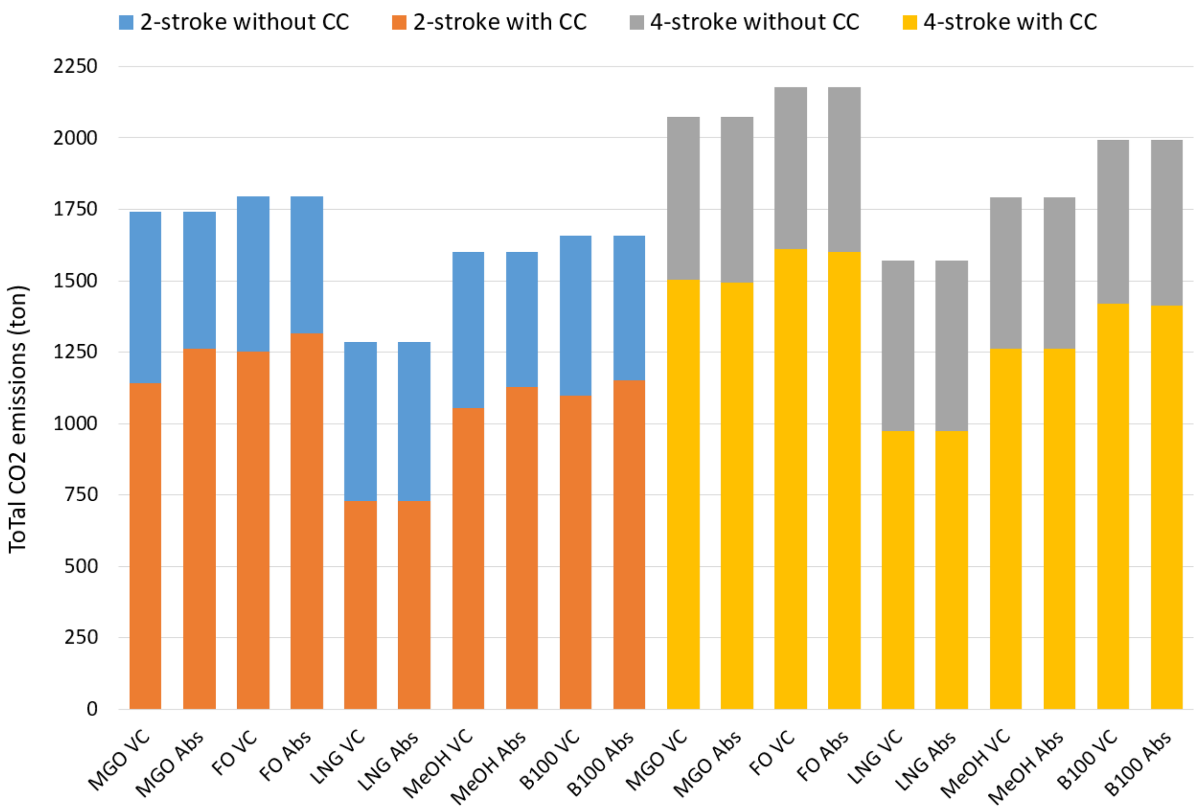

Figure B.1: Total CO_2 emissions of the different combinations for the *Oceanic* case study with and without CC

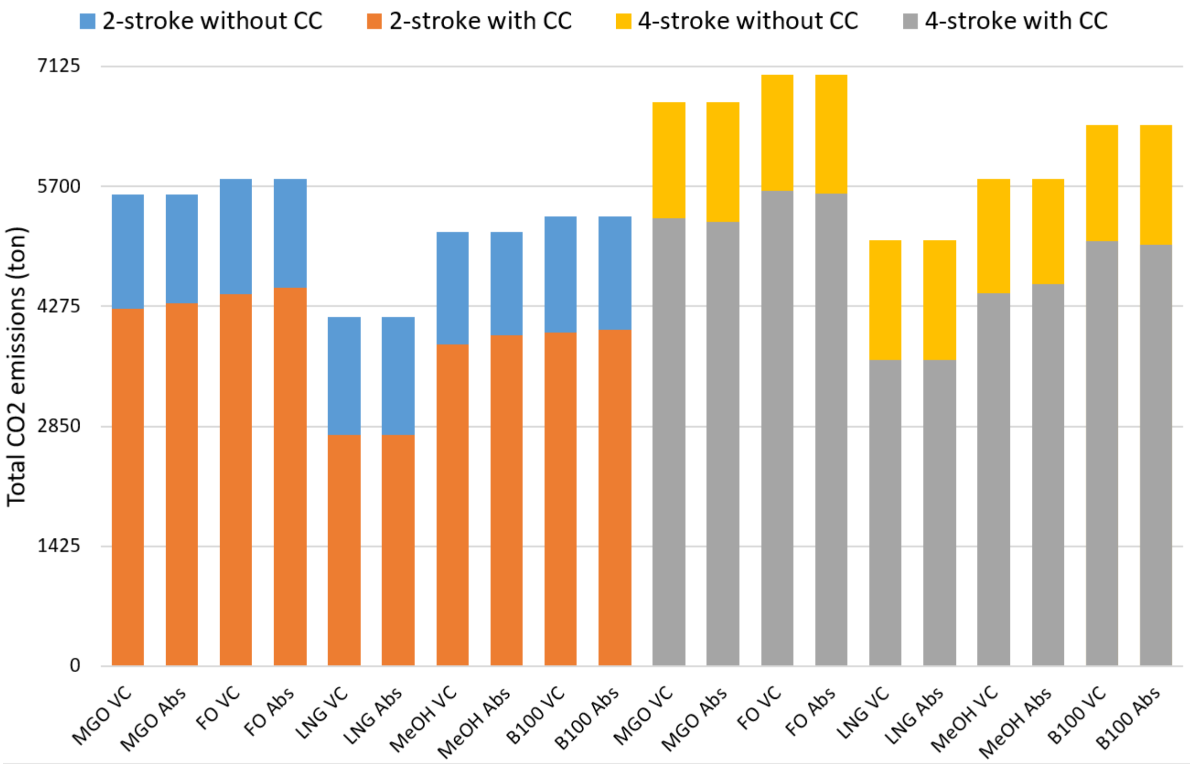

Figure B.2: Total CO_2 emissions of the different combinations for the *Pioneering Spirit* case study with and without CC

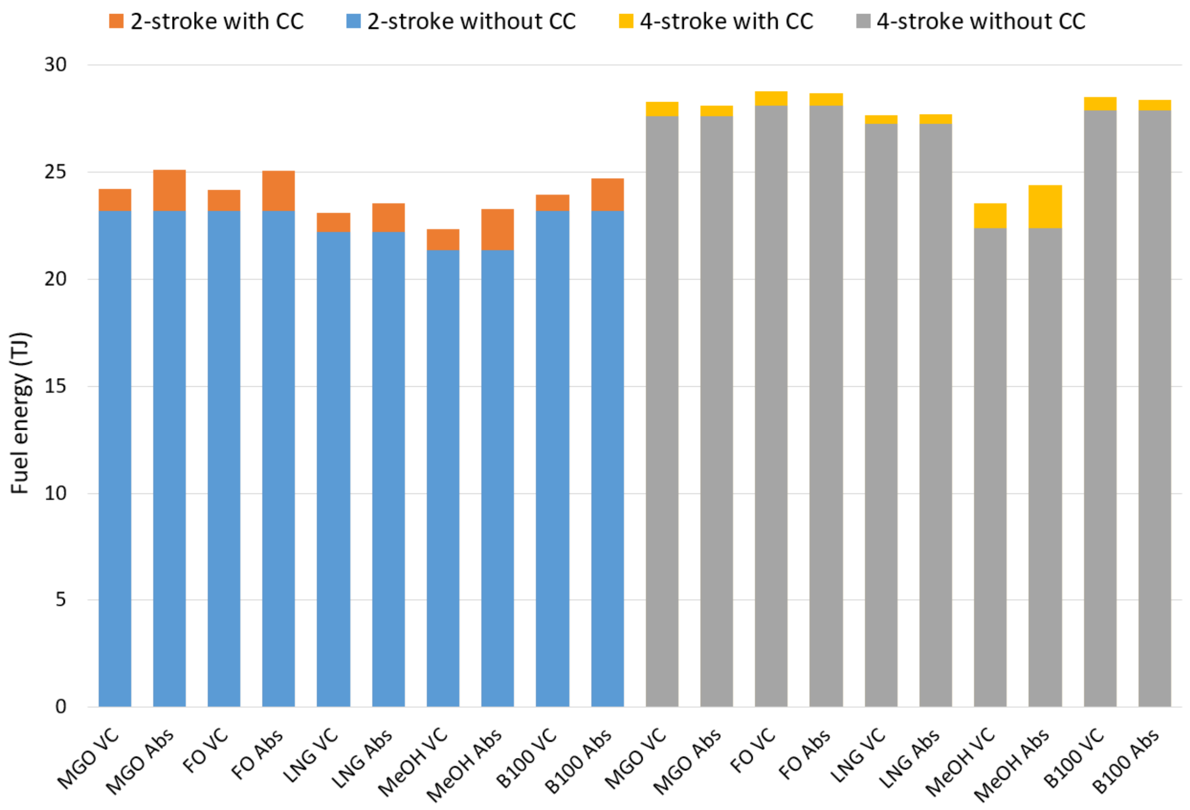

Figure B.3: Total fuel energy of the different combinations for the *Oceanic* case study with and without CC

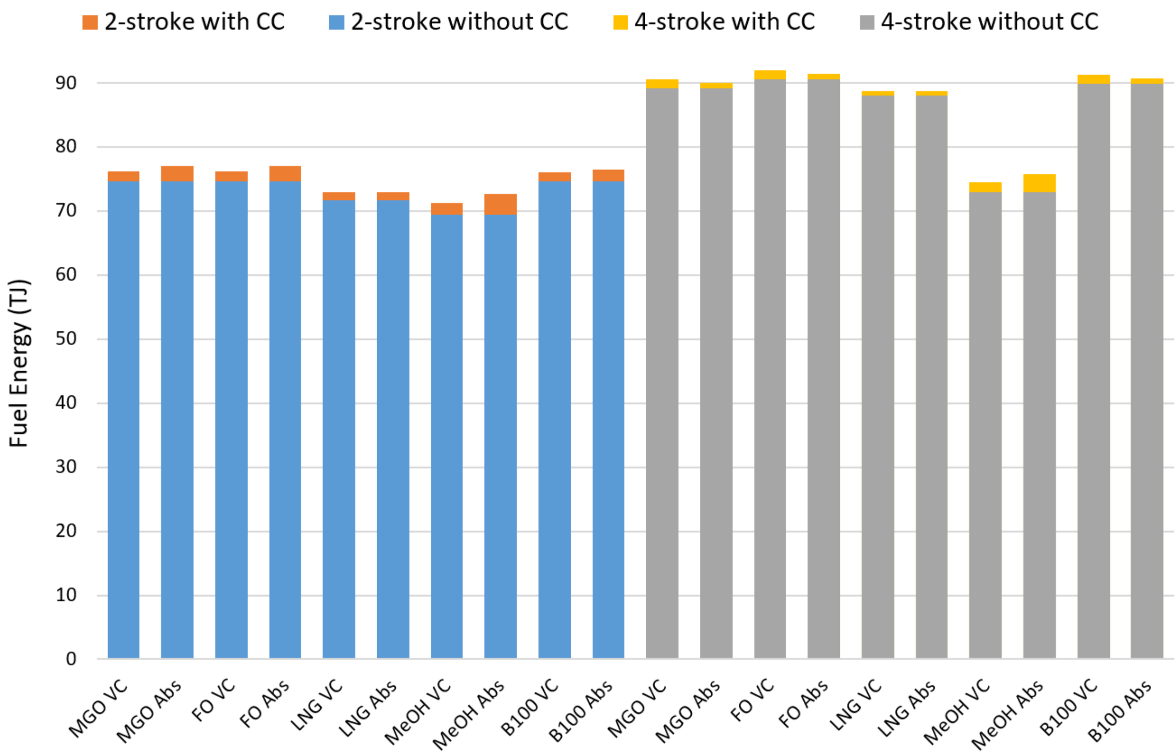

Figure B.4: Total fuel energy of the different combinations for the *Pioneering Spirit* case study with and without CC