Alternative Marine Fuels with Onboard Carbon Capture can Reduce Greenhouse Gas Emissions in the Maritime Sector:

A Life-Cycle Analysis

Arvid Hjortsberg
Malin Wahlström

MAN Energy Solutions

LUND UNIVERSITY

LTH
FACULTY OF ENGINEERING

ISRN LUTMDN/TMHP-24/5586-SE
ISSN 0282-1990

Alternative Marine Fuels with Onboard Carbon Capture can Reduce Greenhouse Gas Emissions in the Maritime Sector:
A Life-Cycle Analysis

Published by
Department on Energy Science
LTH, Faculty of Engineering
Box 118, 221 00 LUND, Sweden

Department of Energy Sience
Lunds Tekniska Högskola
Supervisor LTH: Marcus Lundgren
Supervisor MAN Energy Solutions: Johan Sjöholm
Supervisor MAN Energy Solutions: Henrik Christensen
Supervisor MAN Energy Solutions: Isabeau Zahm
Examiner LTH: Per Tunestål

Abstract

The marine sector contributes significantly to global greenhouse gas (GHG) emissions and a reduction is required in the sector's environmental impact to meet present climate change targets. This thesis conducts a well-to-wake life-cycle assessment of potential decarbonization solutions for the marine industry, aiming to identify the most promising alternative fuels and evaluate the impact of including an onboard carbon capture and storage (OCCS) technology for marine shipping vessels.

The analysis investigates various biofuels, methanol, and marine heavy fuel oil as a reference. Results indicate that methanol offers the highest potential for GHG emissions reduction, but only if all upstream processes are produced sustainably. The effect is greatest when coupled with the OCCS. Biofuels also present future potential for lowering GHG emissions, though the choice of feedstock is critical. Using waste products like used cooking oil has a minimal climate impact, whereas palm oil can result in greater environmental harm than fossil fuels. All evaluated fuels show a reduction in global warming potential when paired with OCCS technology and permanent storage of CO_2 below sea.

Keywords: *environmental shipping, methanol, FAME, biofuels, onboard carbon capture, LCA, alternative marine fuels*

Acknowledgements

We would like to express our deepest gratitude to everyone who helped us through this thesis.

First and foremost we would like to thank our supervisor at Lund University, Marcus Lundgren for helping and supporting us throughout our work. With your positive attitude and great academic experience, you have made our project easier.

We also want to express our appreciation to our supervisors at MAN Energy Solutions, Johan Sjöholm, Henrik Christensen, and Isabeau Zahm. With your expertise and guidance, you have helped us through this journey. Thanks for your constructive suggestions and encouraging advice. This would not have been possible without you.

Contents

Nomenclature

Abbreviations

CO_2	Carbon Dioxide
NA_2SO_4	Sodium Sulphate
$NaHSO_4$	Sodium Hydrogen Sulphate
NO_x	Nitrogen Oxides
SO_x	Sulfur Oxides
0LUC	Zero Land Usage
AGWP	Absolute Global Warming Potential
CCS	Carbon Capture and Storage
CTG	Cradle-to-Grave
dLUC	Direct Land Usage
e-MEOH	Electric methanol
ECO	Emission Control Areas
FAME	Fatty Acid Methyl Ester
GHG	Green House Gas
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
ICE	Internal Combustion Engine
iLUC	Indirect Land Usage
IMO	International Maritime Organisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LNG	Liquid Natural Gas
MEA	Monoethanolamine

MGO	Marine Gas Oil
NaOH	Sodium hydroxide
NG	Natural Gas
OAT	One-At-a-Time
OCC	Onboard Carbon Capture
PM	Particulate matter
RME	Rapseed Methyl Esters
SCR	Selective Catalyst reduction
UCO	Used Cocking Oil
VLSFO	Very Low Sulfur Fuel Oil
WTP	Well-to-Pump
WTW	Well-to-Wake

1 Introduction

1.1 Background

One of the most important issues of our time is the need to reduce the greenhouse gas (GHG) emissions to meet the Paris Agreement's requirements. A major contributor to GHG emissions is the transportation sector. While various modes of transportation exist, none match the energy efficiency of maritime shipping for international trade per shipped kilo. However, despite its high effectiveness, maritime shipping still accounts for nearly 3% of global GHG emissions [1] [2].

1.1.1 The Maritime Transport Sector in Numbers

The maritime transport sector is estimated to account for 80% of the global goods shipped with an annual transported weight of 11 billion tons in 2021. The industry is currently experiencing steady growth despite a decline in transported goods during COVID-19 which grew by 43% between 2013 and 2021. [3] The maritime shipping industry is currently a market with a decline in market competition with the top four carriers controlling half of the global market [4].

1.1.2 Environmental Concerns

Today the maritime shipping sector is powered mainly by fossil fuels like heavy fuel oils (HFO) and marine gas oil (MGO) . A result of the combustion of these fuels is the release of carbon dioxide(CO_2), the biggest contributor to global warming today.

Other emissions released from the combustion of marine fuels are nitrogen oxides (NO_x) and sulfur oxides (SO_x) which have negative impacts on the environment, human health and the biological ecosystem, like for example acid rain [5]. In 2015 the maritime transport sector account for approximately 15 % of the emitted NO_x and 13% of the emitted SO_x worldwide [6].

Additionally, some fuels release particulate matter (PM) during combustion. The release of PM contributes to serious health effects like smog in urban areas, and both indirect and direct consequences to the environment through heating of the atmosphere. [7] The PM emissions from the maritime sector account for approximately 9% of the total global PM emissions. [8]

1.1.3 IMO Regulations

Historically, the marine industry has been largely unregulated when it comes to exhaust emissions and energy consumption. This is still the case for certain geographical areas but the International Maritime Organisation (IMO) has in recent years passed several regulations to limit the emissions from maritime shipping with its 2018 GHG strategy. The strategy has the following main targets:

- Reduce the carbon intensity by 40% by 2030, compared to 2008
- Reduce the total GHG emissions by 50% by 2050, compared to 2008 (Referred to as the "IMO 2050 goal" in the report)

The 2050 goals would require a minimum gross reduction of 75-80% of ship emissions if the current 3.3% annual growth rate is continued until 2050.

IMO has also proposed a more ambitious strategy, the 2023 GHG strategy with the goal of reaching net-zero CO_2 emissions by 2050 [9]. The 2023 GHG strategy has not yet been implemented and is planned to be adopted during the 2028 Marine Environment Committee meeting [4].

Furthermore, IMO has set several global regulations to reduce harmful emissions from the maritime sector. 1st of January 2020 the global upper limit on sulfur content in fuels was set to 0.5% worldwide. HFO where the sulfur content has been reduced to 0.5% is denoted very-low sulfur fuel oil (VLSFO) . In some emission control areas (ECA) the upper sulfur limit in fuel is as low as 0.1%.

NO_x was the first pollutant to be restricted by IMO. The Tier ll compliance was put into use in 2011 and limits the NO_x emissions to 14.4 g/kWh. However, the Tier lll maximum was later implemented to limit NO_x emissions to 3.4 g/kWh which put even more pressure on engine makers. [10]

SO_x emissions from an engine are mainly dependent on the fuel type. A fuel with high sulfur content will emit a higher amount of SO_x during combustion. NO_x emissions are instead a result of the combustion process and the amount mainly depends on the oxygen content and temperature during combustion. [10]

To achieve the goals and comply with the regulations set by the IMO, a wide range of actions need to be implemented. One initial step has been to increase the energy efficiency of engines. Although engines have become increasingly more efficient over the last decade through the use of direct coupling between engine and propeller, intelligent engine operation, and optimized engine design, this alone cannot achieve the set goals. Thus, other measures need to be adopted. Currently, alternative fuels are progressing towards commercial implementation. Examples include liquid natural gas (LNG), biofuels, methanol, and ammonia, which can reduce CO_2 emissions compared to standard fossil fuels [11]. However, there are limitations associated with these alternative fuels. Some still require a mix of renewable and fossil sources, some contain carbon and thus release CO_2 upon combustion, and others are too immature for large-scale adoption.

Projections indicate that to achieve IMO's 2050 goal alternative fuels can not alone fulfill the goal, other sustainable innovations are necessary. A new promising technology is the carbon capture and storage (CCS) technology to reduce CO_2 emissions [12]. Using a CCS aboard shipping vessels could therefore be a solution to achieve the IMO's 2050 goals.

1.2 Previous Research on CCS in the Maritime Sector

Several studies on the topic of carbon sequestration from ships have been written with most of the studies published in recent years since IMO set the new greenhouse gas goals in 2018. This chapter will mention a few studies relating to this report and the topic of carbon capture aboard marine shipping vessels.

Life-Cycle Assessment and Costing of Fuels and Propulsion Systems in Future Fossil-Free Shipping. In this study, several alternative propulsion methods for marine shipping vessels are considered and evaluated using a life cycle perspective. The study includes nine systems (cases) and several fuels, energy storage methods, and CO_2 abatement methods are analyzed in depth. The unique aspect of the report is the inclusion of the entire cradle-to-grave aspect of each system. This allows the authors to incorporate the entire life cycle in the conclusion. Case 2 in the study includes a post-combustion CCS and runs on methanol. [1]

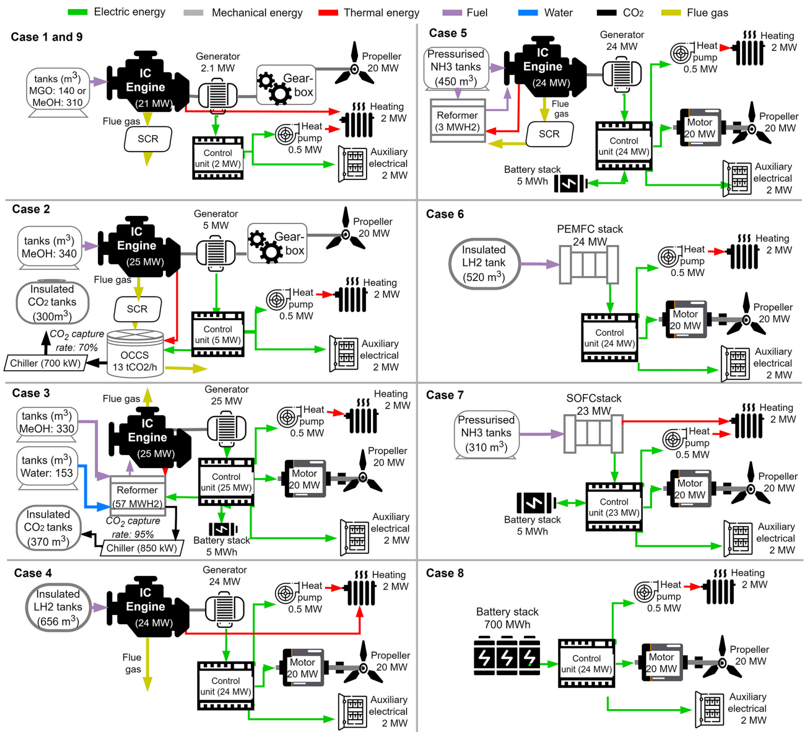


Figure 1: Systems from Life-Cycle Assessment and Costing of Fuels and Propulsion Systems in Future Fossil-Free Shipping [1]

The LCA results (Figure 2) from the study indicate that all of the alternative pathways have the potential to reduce the global warming impact. The final conclusion of the report is that the decarbonization methods studied increase the lifetime cost by 2.5-4 times. Fuel cells perform better than ICE in terms of cost, environment, and energy utilization over a lifetime despite the higher capital cost (this is sensitive to operation hours per year). Several of the ICE systems are associated with high emissions of NO_x and ICE' operating on hydrogen can mitigate a lot of these emissions resulting in a more environmentally friendly operation. [1]

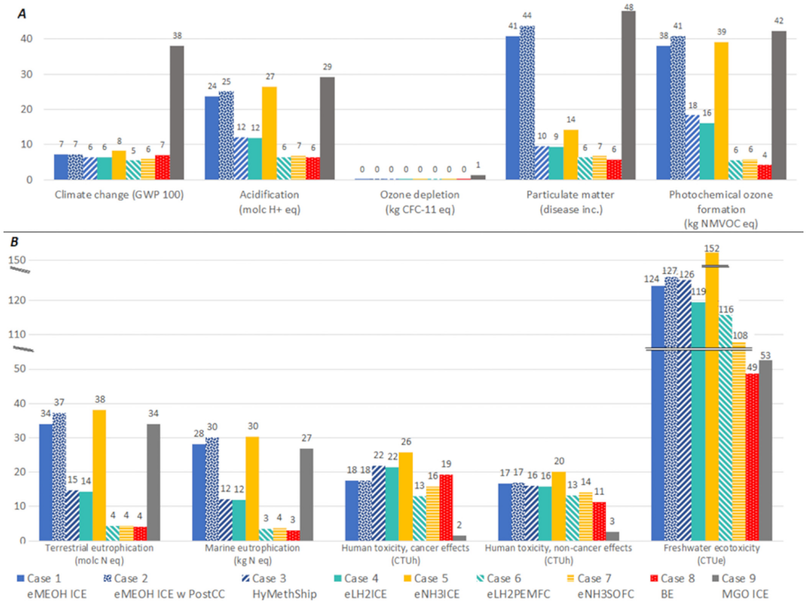


Figure 2: Results from Life-Cycle Assessment and Costing of Fuels and Propulsion Systems in Future Fossil-Free Shipping [1]

Technoeconomic evaluation of post-combustion carbon capture technologies on-board a medium-range tanker. The study aims to differentiate different post-combustion CCS methods for a medium-range tanker. The technologies considered are; absorption with amine and ammonia, Cryogenic, and Membrane CCS.

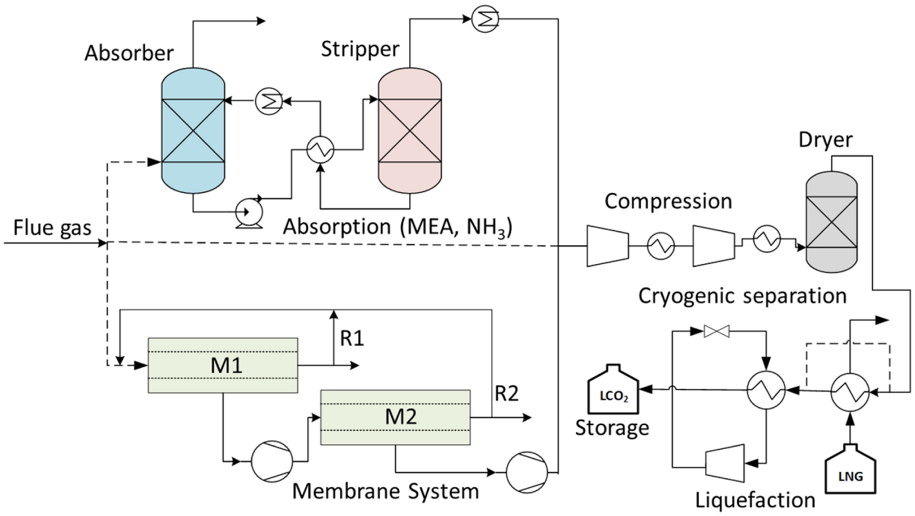


Figure 3: Flow chart of medium-sized tanker [13].

The systems are then evaluated by simulation in MATLAB and Aspen Plus to answer which system is the best performing regarding cost, captured CO_2, etc. Two fuels are compared; HFO and LNG. The study concludes that the amine-based carbon capture system performs best in regards of the CO_2 abatement costs. Key points of interest extracted from the results are the effective capture of CO_2 of 75% correlates with an increase in onboard weight of 3.3% and an increased fuel consumption of 19% during a round trip. The study also concludes that LNG performs better than the HFO when used with the amine-based system in terms of fuel economy and total emissions. [13]

Optimal capacity design of amine-based onboard CO_2 capture systems under variable marine engine loads The study aims to design an onboard carbon capture (OCC) system that performs well over a wide range of engine loads while selecting a proper system capacity. To identify the optimal capacity of the OCC system, five amine-based OCC systems with different capacities are developed. The performance results are quantified in terms of energy requirements, potential CO_2 reduction rates, and capture costs. [12]

CO_2 concentration varies with fuel type, engine type, and the load. The energy required to regenerate the solvent in the stripper (specific reboiler duty) is the main energy consumption. A higher load gives higher specific reboiler duty [12]

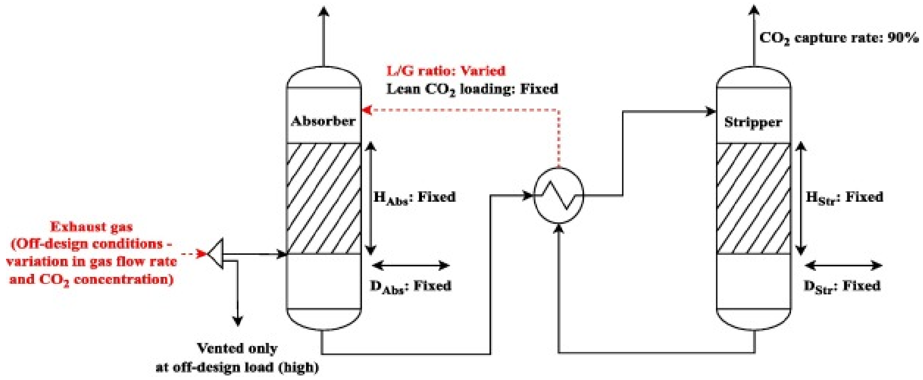


Figure 4: Variable design parameters [14]

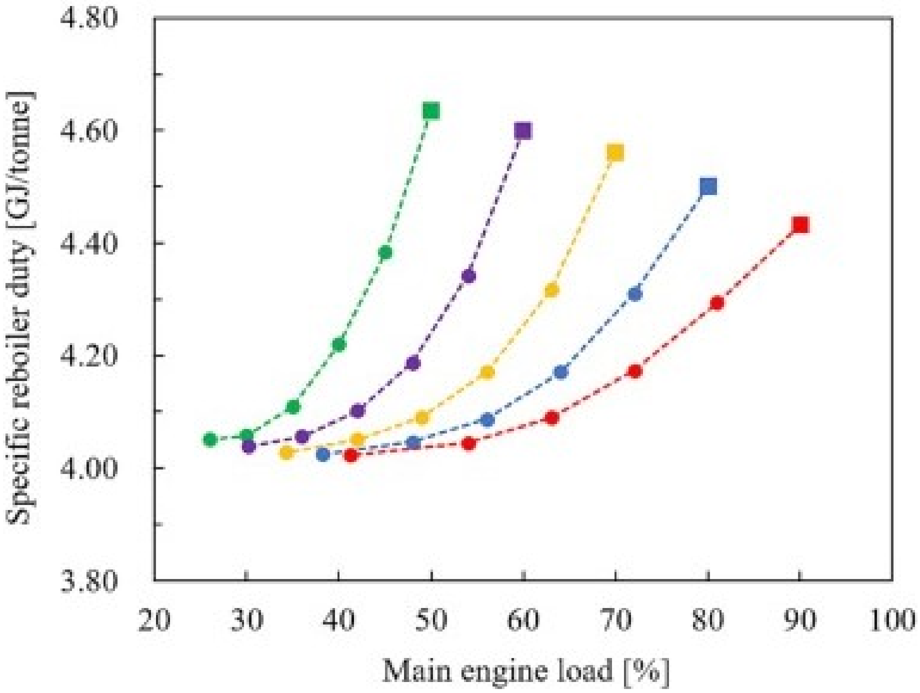
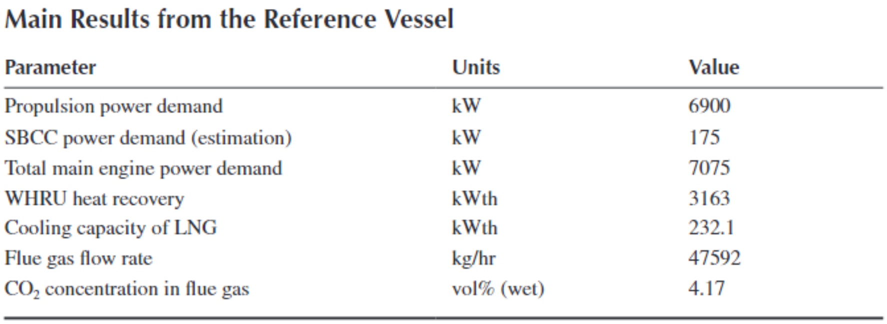


Figure 5: Boiler duty vs engine load [12]

Figure 6: Figures from Life-Cycle Assessment and Costing of Fuels and Propulsion Systems in Future Fossil-Free Shipping [12]

Special Case Studies in Sustainable Carbon Capture In this case study a hypothetical vessel with LNG -fueled engine is discussed. The reference vessel is assumed to operate at 75 % engine load of the main engine. The absorber has a packing height of 7m each. Here it is stated that the two main limitations on the capture rate are the cooling capacity of the LNG and the heat in the flue gasses. This system is then able to have a capture rate of 80.2%. The main results from the reference vessel and main results from the CO_2 capture are shown in tables 7 and 8.



Main Results from the Reference Vessel

Parameter	Units	Value
Propulsion power demand	kW	6900
SBCC power demand (estimation)	kW	175
Total main engine power demand	kW	7075
WHRU heat recovery	kWth	3163
Cooling capacity of LNG	kWth	232.1
Flue gas flow rate	kg/hr	47592
CO_2 concentration in flue gas	vol% (wet)	4.17

Figure 7: Results from Reference Vessel Special Case Studies in Sustainable Carbon Capture [15]

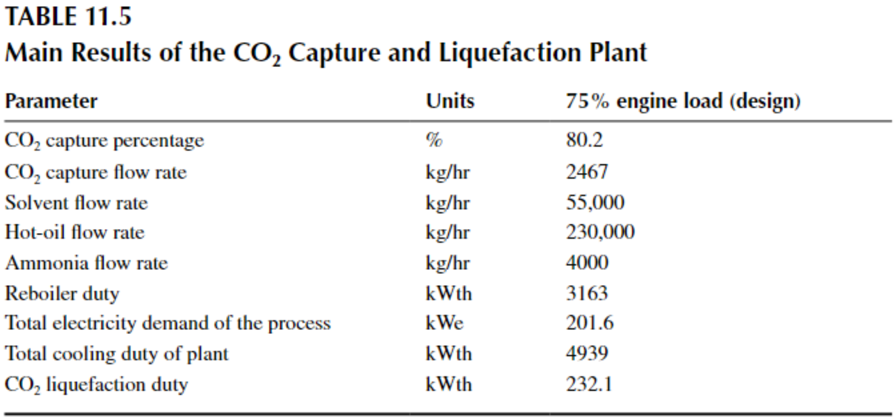


TABLE 11.5
Main Results of the CO_2 Capture and Liquefaction Plant

Parameter	Units	75% engine load (design)
CO_2 capture percentage	%	80.2
CO_2 capture flow rate	kg/hr	2467
Solvent flow rate	kg/hr	55,000
Hot-oil flow rate	kg/hr	230,000
Ammonia flow rate	kg/hr	4000
Reboiler duty	kWth	3163
Total electricity demand of the process	kWe	201.6
Total cooling duty of plant	kWth	4939
CO_2 liquefaction duty	kWth	232.1

Figure 8: Results from Special Case Studies in Sustainable Carbon Capture [15]

The conclusion by the authors is that there is a high level of synergy between the onboard carbon capture and the LNG, thus lowering the cost of operation significantly. Due to space limitations, specific boiler duty is not optimal. A clear reduction in CO_2 abatement cost can be achieved if the engine is operated at optimal levels, avoiding operation at low engine loads. [15]

Energy assessments of onboard CO_2 capture from ship engines by MEA-based post-combustion capture system with flue gas heat integration The study aims to analyze the feasibility of an onboard carbon capture unit using numerical simulation models together with supervised machine learning to estimate the operation parameters for the OCCS. The study concludes that the exhaust gas from the engine is not sufficient to heat the boiler sufficiently for a capture rate above 50%. An afterburner is utilized to heat the flue gasses to a sufficient amount, receiving a capture rate up to 90%. The fuel consumption is increased by 6-9% for LNG and 8-12% for diesel. [16].

1.3 Purpose and Approach

This master thesis is a study conducted together with MAN Energy Solutions. The purpose is to investigate the climate impact of different alternative fuels together with the use of an onboard CCS. The study will use data from a MAN engine coupled with a theoretical CCS unit. The climate impact assessment will be conducted using a life-cycle-assessment according to the methodology outlined in ISO:14044. The investigated systems are as follows:

- System 1: VLSFO + CCS
- System 2.a) Biofuel from palm oil + CCS
- System 2.b) Biofuel from rapeseed oil + CCS
- System 2.c) Biofuel from soybean + CCS
- System 2.d) Biofuel from used cooking oil + CCS
- System 3.a) Green methanol + CCS
- System 3.b) Methanol from natural gas + CCS

In an LCA a studied system is called *product system*. For consistency, the seven systems will from now on be called that. The primary question addressed in this thesis is the following:

Which of the systems has the best potential to fulfill the IMO 2050 goal of 50% GHG reduction compared to 2008?

To answer this question, the two following sub-questions will be investigated:

- *Which alternative fuel has the least impact on climate change?*
- *Is the CCS a possible innovation to reduce CO_2 emissions in the maritime sector?*

1.4 Outline of the thesis

This thesis consists of seven chapters. The following chapter, *Life Cycle Assessment Framework* describes the life cycle assessment (LCA) framework. This includes the working steps and the principles of an LCA. The section is followed by a description of the impact categories concerned in the thesis.

Chapter 3, *Case Study Description*, describes the studied product systems. The chapter provides an overview of the fuel production phases and how they work. Also, a description of each component included in the product systems will be described and motivated.

Chapter 4, *Applied Methodology*, describes the method used, which consists of two parts. The first part describes the process of modeling the product systems. The second part describes the LCA process applied, including descriptions of all choices made and data used in the thesis.

The results of the climate impact assessment are provided in Chapter 5, *Results.* This chapter shows the product systems' impact on specific impact categories, both with and without the influence of the CCS. Also, a sensitivity analysis and a Monte Carlo simulation are provided. The results are then discussed in Chapter 6.

In Chapter 7, a conclusion is drawn and the answers to the research questions are provided. Finally, recommendations for future research are provided.

2 Life Cycle Assessment Framework

To answer the research question of this study an LCA has been applied. LCA is a method outlined by the ISO 14040 and 14044, [17] [18] which is used to examine the environmental impacts and aspects of a product system. This chapter introduces a brief introduction to the LCA approach.

2.1 General Description

In the introduction of ISO 14040, the approach is described as follows:
LCA addresses the environmental aspects and potential environmental impacts(e.g. use of resources and the environmental consequence of releases) throughout a product's life cycle raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (i.e. cradle-to-grave). [17]

2.1.1 Principles of LCA

While implementing an LCA there are several fundamental principles to consider according to ISO 14040. Some of these principles will be discussed in this section.

One of the most essential principles of an LCA is the life cycle perspective. An LCA examines a product's complete life cycle, starting from the extraction and procurement of raw material to energy and material production, to manufacturing, utilization and finally to disposal at the end of its life. This extensive approach allows for a systematic analysis of each stage and process, enabling the identification and potential avoidance of any transfer of environmental impact from one stage to another or between individual processes.

Furthermore, while performing an LCA the environmental impacts and aspects should be in focus. Other impacts like economic or social aspects are usually not within the scope of an LCA and therefore other supplementary tools may be used to involve these aspects.

Moreover, the LCA approach is relative and is built around the functional unit. The functional unit is the useful output of the product system studied. All other processes analyzed in the system are then related to the functional unit, to enable the execution of the LCA.

Finally, transparency and comprehensiveness are important during the LCA process. As a result of the complexity and width of the LCA as a tool, the importance of transparency throughout the process increases, to ensure a proper interpretation of the results. Likewise, it is important with comprehensiveness. By comprehensively considering all factors of natural environment, human health, and resources, the study can identify possible trade-offs. [17]

2.2 The LCA Process

According to ISO 14040 an LCA consists of the four following phases:

- 1) The goal and Scope phase
- 2) The inventory assessment phase
- 3) The impact assessment phase
- 4) The interpretation phase

The first phase, the goal and scope definition is interpreted to ensure that the LCA maker defines the scope and intended use of the LCA. In this stage decisions like the system boundaries, the functional unit and geographical area are determined. The second stage, life cycle inventory analysis (LCI) phase includes data collection of needed data to fulfill the goals of the study. The inventory should include input and output data for each process of the studied system. The life cycle impact assessment phase (LCIA) is the third step and its purpose is to give more details to help understand the environmental impacts of the processes in the study. Lastly, the life cycle interpretation phase is applied. In this phase, the results from the LCI and LCIA will be discussed, analyzed, and summarised. Here conclusions can be drawn to from the basis of decisions or recommendations according to the goal and scope definitions. [17]

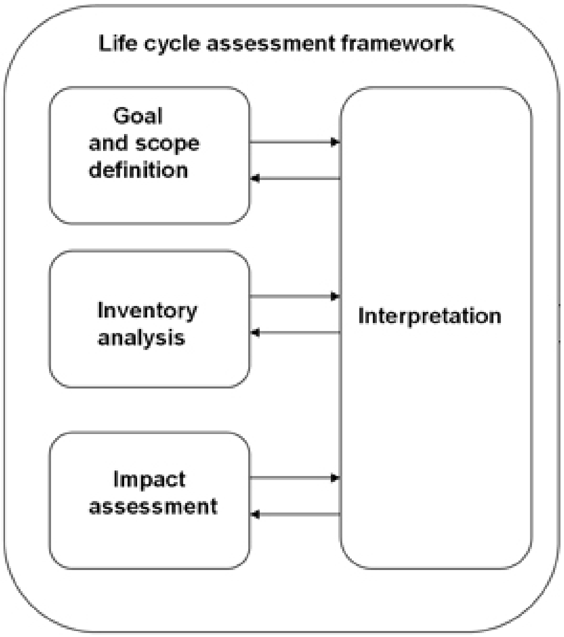


Figure 9: Working principles of the LCA process. [14]

LCA is an iterative process and therefore each phase utilizes findings from the other. This is illustrated in figure 9. This iterative approach, both within each phase and across the entire assessment, enhances the comprehensiveness and reliability of the study and its outcomes. [17]

2.3 Environmental Impact Categories

To systematically interpret the results of an LCA, three factors have been developed. The purpose of these factors is to categorize emissions and resources used by the studied system and translate them into entities that are aimed to protect. These factors are called areas of protection and are divided into human health, natural environment, and natural resources. Human health is measured by mortality, while the natural environment is measured by the disappearance of species and the loss of biotic productivity. Natural resources are more difficult to measure. This area of protection can be divided into subcategories such as water resources, land resources, metal ores, or fossil fuels. [11]

All emissions and resources used along the studied product system pathway affect the environment in some way. For example, the release of CO_2 contributes to climate change, and SO_x emissions lead to acidification. These environmental issues are called midpoint impact categories, whereas the areas of protection are called endpoint impact categories.

The relation between the different types of impact categories is shown in Figure 10. It illustrates that the emissions and resources used from the life cycle inventory results contribute to some identified environmental issues. Consequently, these environmental issues affect the areas of protection.

When implementing an LCA, the use of only midpoint categories or both mid- and endpoint categories can be employed, as long as this is clarified in the report. The advantage of using only midpoint categories is that they are easier to quantify; however, the results might be more difficult to use and interpret. Using endpoint impact categories has the advantage that their units are easier to understand since they are measured in clear terms. On the other hand, it is challenging to translate midpoint categories to endpoint categories, which can result in misleading interpretations. [11]

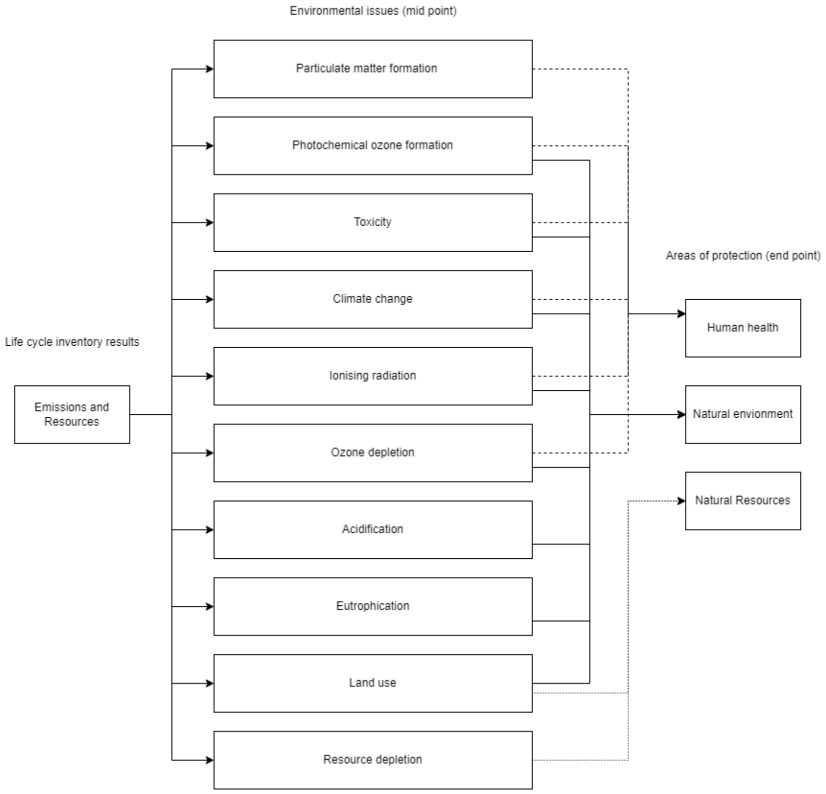


Figure 10: The relation between mid- and endpoint impact categories. Figure inspired by [11]

The main midpoint impact categories studied in this report will be explained in the following part of this section.

Climate change Climate change affects both human health and the natural environment. Human health is directly affected by climate change through heat waves and other extreme weather and indirectly e.g. by increasing infections and diseases. The natural environment is affected by the loss of species due to increasing temperatures. Climate change is an indicator of the potential global warming resulting from the release of greenhouse gases into the atmosphere. [11]

Different greenhouse gases have different effects on global warming depending on their radiative properties and the lifespan of the gas released in the atmosphere. Global warming potential (GWP) measures the radiative properties over a specific time period relative to CO_2 for various emissions. To add the lifespan properties a number can be added after the GWP. For example, GWP20 means that the effect of the warming of the earth over 20 years. The most common is using GWP100. The GWP is measured in the unit tonnes CO_2 equivalents. For example, CO_2 has by definition GWP 1 regardless of the time period used. Instead, the GWP100 for methane equals 28, meaning 1 tonne of methane affects the environment as much as 28 tonnes of CO_2 over a time period of 100 years. This is because methane absorbs more energy than CO_2, even if the lifetime is shorter. Over the total period of 100 years, the warming effect is still higher, resulting in a higher value of GWP100. [19]

To calculate the GWP over a time period the absolute global warming (AGWP) is needed. It expresses the amount of radiative forcing over the time period caused by the emission of 1 kg of GHG. This is expressed in $Wm^{-2} \cdot yr \cdot kg^{-1}$. With the AGWP the GWP for a GHG (x) at the time horizon (TH) can be recalculated from the following equation [20]:

$$GWP_{x,TH} = \frac{AGWP_{x,TH}}{AGWP_{CO_2,TH}} \tag{1}$$

The equation provides the GWP over a specific time horizon in kg CO_2 eq/kg GHG. The number for $AGWP_{CO_2,TH}$ and $AGWP_{x,TH}$ can be found in the latest Intergovernmental Panel on Climate Change (IPCC) report. [21]

This report mainly focuses on climate change so the following impact categories to consider will be briefly mentioned.

Stratospheric ozone depletion leads to damage to human health through the increase in UVB radiation and therefore an increase in skin cancer and cataracts. This is mainly caused by the release of chemicals with bromine groups or chlorine that interact with ozone. [20]

Ionizing radiation is increased by emissions of radionuclides from nuclear fuel. These particles can damage human health through DNA damage. [20]

Fine particulate matter formation is mainly characterized by fine particulates less than 2.5 μm released in the atmosphere. These can cause damage to human health through respiratory issues. [20]

Photochemical ozone formation is the formation of ozone from mainly NO_x or NMVOC emissions. These can damage human health as ozone can inflame airways and damage the lungs. Ozone can also cause harm to vegetation with a decrease in growth and seed production. [20]

Terrestrial acidification is the change in acidity in the soil from inorganic compounds such as SO_x, NO_x or NH_3. This can damage terrestrial ecosystems by making the soil less usable by plant species. [20]

Freshwater eutrophication is the increase in nutrients in freshwater that allows for an increase in algae growth that can potentially disturb the local ecosystems. This mainly comes from emissions of phosphorus and nitrogen. [20]

Toxicity accounts for the accumulation of toxic chemicals in the food chain and causes damage to both the ecosystem and human health. [20]

Water use is water usage that causes the water to evaporate. Unsustainable water use can cause damage to human health and ecosystems. [20]

Land use is the land usage that ultimately can cause a loss of species. This includes the direct, local impact of land use on local species. This is affecting local species by a change of land cover and ultimately loss of habitat. [20]

Mineral resource scarcity is divided into several levels. The initial effect is the decrease of a specific mineral. It is estimated that extraction will affect the total available minerals and ultimately affect the scarcity of natural resources. [20]

Fossil resource scarcity evaluates how fossil extraction can lead to a future increase in fossil resource extraction ultimately causing damage to natural resource availability. [20]

2.4 Allocation, System Expansion or Avoided Burden

Allocation is needed when a process has multiple useful outputs. For example, a crude oil refinery produces multiple types of oils from crude oil not only HFO that will be studied in this thesis. This problem can be solved by either use allocation or system expansion. Allocation means the burdens are allocated between the products in some way. This can for example be done by physical characterization, like by mass, volume, or energy content. In the example, this could mean that emissions from the refinery are allocated depending on the energy content in the oils or the mass of the oils.

To avoid allocation problems it is possible to expand the system boundaries. This means that all the burdens are included by expanding the system boundaries to include all affected processes. [11] In the refinery example, this means that the emissions from the whole crude oil refinery would be included not only the one representing the the HFO in the studied product system. In ISO14044 it is stated that if it is possible allocation should be avoided by system expansion. [18]

Von de Assen et al. [22] discuss a third concept regarding LCA's in carbon capture studies. He explains that there are common pitfalls that should be avoided. One of these is the so-called *avoided burden*. This concept appears when multiple useful outputs in a process occur, but only one is seen as a reason for operating. Emissions from other processes are taken away from the system's emissions because it is assumed that these processes are replaced and their environmental burdens are avoided.

An example of avoided burden is the production of methanol through the synthesis of captured CO_2 and H_2, which is illustrated in Figure 11. A CCS is placed at an electricity-producing power plant to capture the CO_2. The methanol is then produced with the CO_2 and H_2. This product system has two useful outputs, electricity and methanol. Depending on what is seen as the main output the results for avoided burden look different. For example, the methanol producer gets a surplus of electricity which avoids other electricity production. On the other hand, from the electricity producers' perspective, methanol is seen as a surplus, which can be seen as avoiding burdens from other methanol producers. [22] states that this approach is inappropriate since it does not distribute the environmental burdens among all processes, but assigns them only to one. Instead, allocation or system expansion are better choices to obtain numbers representing the whole picture. [22]

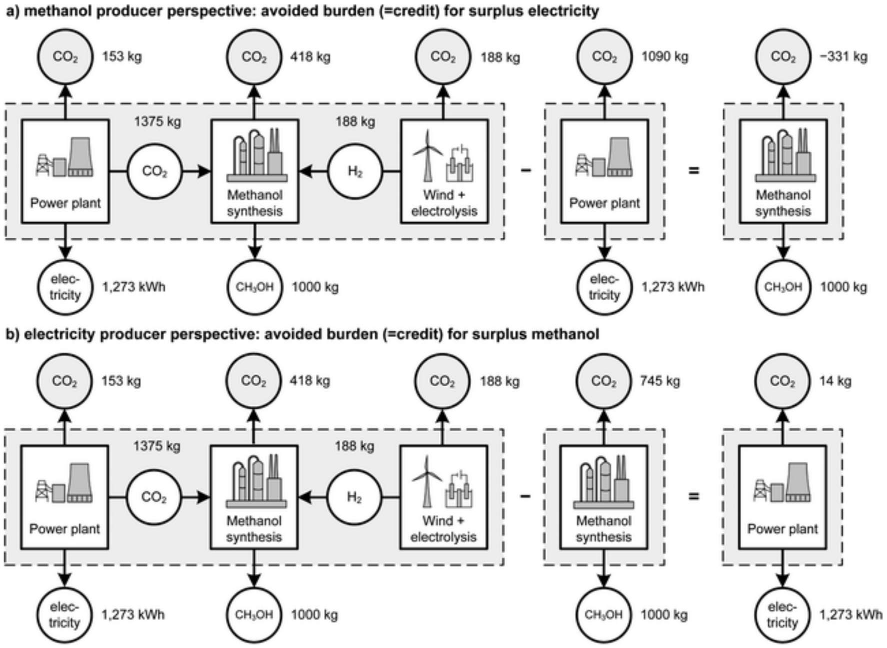


Figure 11: Avoided burden result from different perspectives [22]

3 Case Study Description

In this chapter, the product systems chosen will be described. The seven systems look similar including the same components, but with minor differences. A simplified model of the product systems was made and is shown in figure 12. As shown in the figure the systems include an engine, two flue gas treatment components, and an onboard carbon capture. The engine produces useful mechanical work that controls the shaft on the ship. The waste heat produced from the combustion will be used in the carbon capture system. The CCS and the flue gas treatments also require some electrical energy, which will be produced by a generator, which is driven by the engine. Furthermore, there are auxiliary systems onboard that require electricity, which will be delivered by the generator. Each of the processes in the product systems will now be further described and motivated.

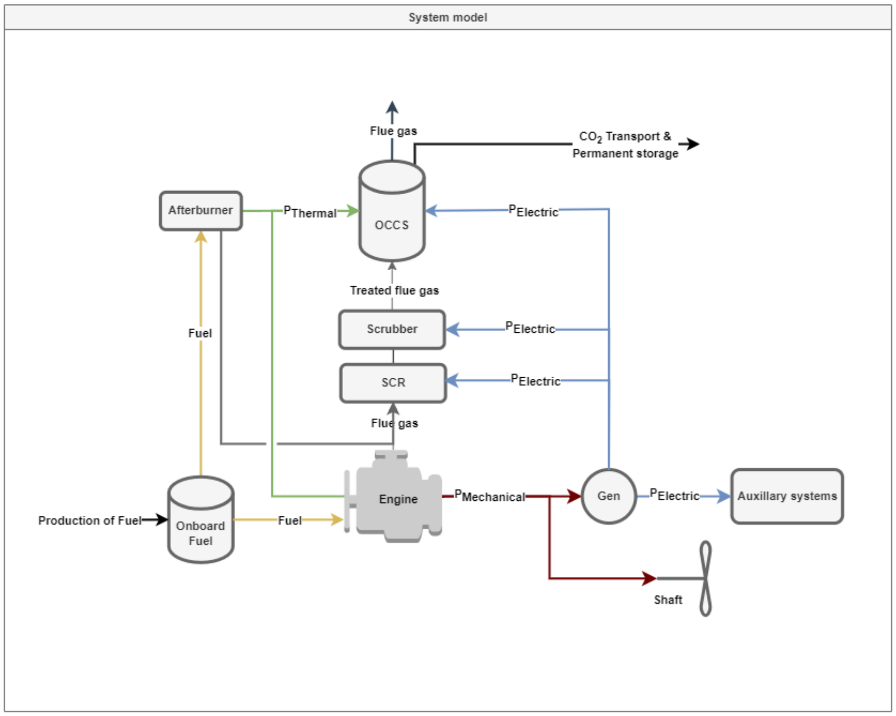


Figure 12: Simplified picture of the studied systems

3.1 Fuel

Before the fuel can enter the engine to power the ship, the fuel needs to be produced and transported to the ship. The production pathways for the fuels will be described in this section. Product system 1 will work as a base case and will run on today's most common marine fuel which is VLSFO [23]. Product systems 2 a) to 2 d) run on a biofuel called Fatty Acid Methyl Ester (FAME). The difference between the product systems is the feedstock. Lastly, the product systems 3.a) and 3.b) consist of methanol, with two different production pathways. The fuels in this study were chosen because they can be combusted in MAN's engines. The different feedstocks were selected to observe the impact of the production phase.

3.1.1 VLSFO

VLSFO is a fossil fuel made from crude oil. After extraction of crude oil various oils can be separated through atmospheric distillation and vacuum distillation, which is made at a crude oil refinery. During these processes, the crude oil is heated and separated depending on their densities. The heaviest residual oils from the refinery are called HFO and are primarily used in the shipping industry. As mentioned the fuel combusted at sea needs to contain a maximum sulfur content of 0.5 wt%. To reduce the fraction of sulfur in HFO two processes can be used; direct or indirect hydrotreatment. Direct hydrotreatment is a process used to directly remove the sulfur from heavy oil residues. This can be managed through e.g. hydrodesulfurization, hydrotreating, or hydrocracking. These processes involve the use of hydrogen gas under high-pressure conditions to change the molecular structure in the HFO. Indirect hydrotreatment is instead achieved through mixing of low-sulfur and high-sulfur components to obtain a specific sulfur content. The low sulfur component has either been hydrotreated before or contains low sulfur from the beginning. [24] The pathway from crude oil extraction to the onboard fuel is shown in figure 13. It is worth noticing that the picture is simplified since the process of crude oil becoming VLSFO can look in many different ways. Each step of the process requires energy and causes pollutants as shown in the figure.

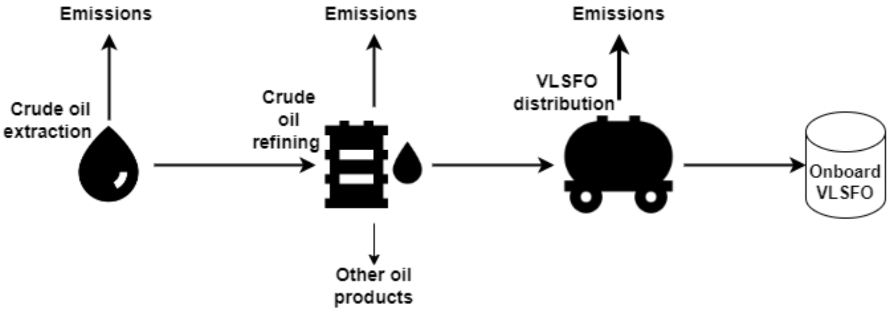


Figure 13: Simplified picture of the production pathway of VLSFO

3.1.2 Biofuel

Biofuels is a broader term to describe fuels derived from biomass; e.g. plants, waste, algae, or animals. [25] There are three generations of biofuels to consider. First-generation biofuels use already cultivated plants and vegetables as feedstock, normally used in other industries like the food industry. The second generation comes from cellulosic biomass that can be grown on land not suitable for row crops. This biomass can come from grass, trees, or crop residue. The third generation of biofuels is made from oil-producing algae [26].

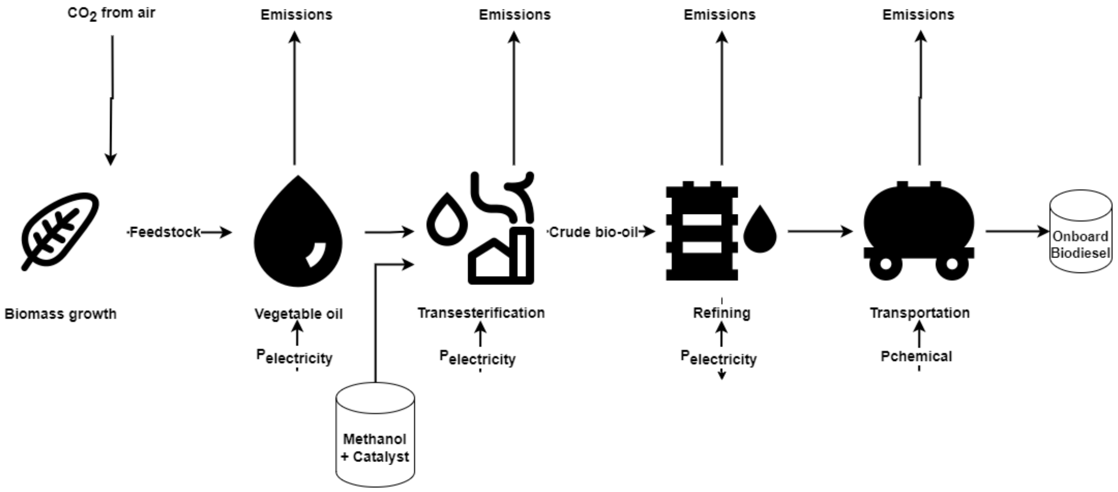


Figure 14: Simplified picture of production pathway for biodiesel

The different generations of biofuels come with different opportunities and challenges. This report will only consider a first-generation biofuel; biodiesel, more specifically FAME. The production processes for each fuel type are different and require different catalysts, processes, and additives. This report only considers various kinds of FAME, since FAME is considered as one of the most realistic biofuels for the maritime industry [27] [28]. FAME is produced from vegetable oils, yellow grease, or used cooking oils or animal fats. This is done through transesterification where fats and oils are converted into biodiesel with glycerine as the byproduct. The input products are usually mixed with a short-chained alcohol (usually methanol) that reacts with the oil or fat. A catalyst is required and can be different materials, the most common are sodium hydroxide or potassium hydroxide. [29] See Figure 15 .

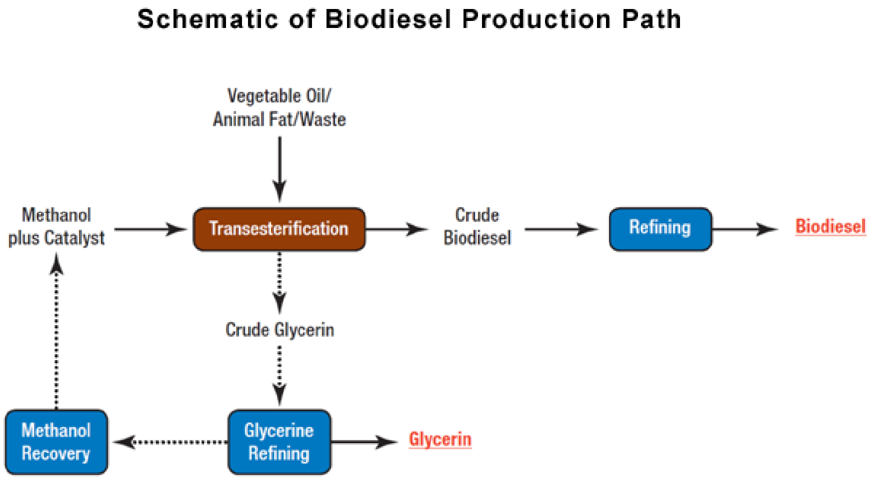


Figure 15: Schematic over FAME-production [29]

The most common feedstock in the EU is rapeseed oil or sunflower oil, while USA uses soybean, corn, and rapeseed oil as its main feedstock. The initial feedstock will affect the properties of the final product with feedstocks being either unsaturated or polyunsaturated. The feedstock should match what is *best* for the intended purpose.

Biodiesel can be used in many different concentrations, denoted as BX or BDX ($X = \%biodiesel$), with concentrations from 2% up to 100%. Risks with using high concentrations of biodiesel include hose and gaskets breaking down. B100 fuels are not currently well supported for the personal consumer but farm equipment and ship engines that allow B100 exist and are getting more common [29].

Biofuels are widely considered to be a low-emission alternative to fossil fuels. The environmental burden of a biofuel is not so straightforward to calculate and several concepts need to be addressed before an impact can be calculated.

Carbon Neutrality or CO_2 Uptake The emissions from biofuels during combustion are typically lower than petroleum diesel. This comes from the mass balance of carbon. The biomass will store some amount of carbon and instead of allocating the *negative* CO_2 during plant growth, it is allocated during the combustion of the fuel. The CO_2 emissions are therefore computed as negative CO_2 emissions during combustion [29]. This is the concept of carbon neutrality. There is however debate whether the assumption of CO_2

balance should be accepted or not. The main reasoning is that land would probably grow crops anyway and the CO_2 from biogenic CO_2 should only be accounted as negative if the fuel has contributed to additional growth of biomass [30]. This can further be motivated by the fact that the CO_2 uptake potential in harvested crops is usually far lower than the CO_2 uptake potential of native plants and vegetation. [31]. To compensate for this the land use change is accounted for each feedstock. This is a way to try and account for the removal of native vegetation.

Land Usage Change Is a measurement of how the growing of crops relates to the increase in the transformation to farmland from other biospheres. There are three ways to assess land usage impact; zero land usage (0LUC), direct land usage (dLUC), and indirect land usage (iLUC).

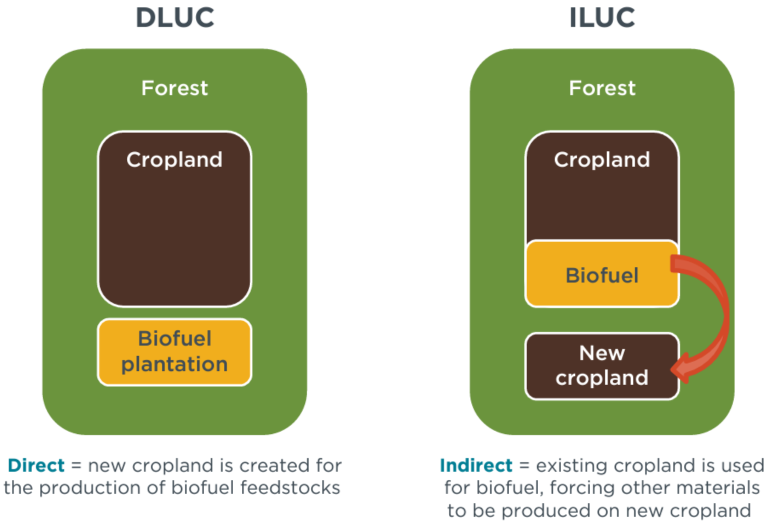


Figure 16: DLUC vs ILUC [32]

The 0LUC does not consider the impact of land use change at all. dLUC is the impact associated with new farmland being constructed to allow for the growth of biofuel and is illustrated to the left in Figure 16. The iLUC considers land required that is not directly related to the cultivation of the crop and is illustrated to the right in Figure 16. Estimating the impact caused by disturbing native ecosystems or biomass supply chains is a complex topic with large deviations in the estimations occurring [33]. The land usage change is not exactly measurable so the land usage change emissions are estimated based on several factors [32] and can potentially be far lower than the actual value [30] [34].

Four different feedstocks for biodiesel are considered in this study. System 2b) and 2c), from rapeseed, (called rapeseed methyl esters (RME)) and soybean, are the most common feedstocks in Europe and the US, which are the geographical areas chosen. Furthermore, system 2a) palm oil and system 2d) used cooking oil (UCO) are included to represent a possible worst and best-case scenario for biodiesel. [35]

3.1.3 Methanol

Methanol is today known as a renewable energy source and is considered a promising alternative fuel, to achieve carbon neutrality [36]. Today methanol is mainly produced from syngas with natural gas (NG) as a feedstock. [37]. Methanol is generally created by steam-reforming natural gas to produce a synthesis gas. In the steam-reforming process, natural gas reacts with steam or CO_2 to create the syngas, which contain carbon monoxide and hydrogen. The chemical reactions look as follows:

$$CO_2 + CH_4 \rightarrow 2CO + 2H_2 \tag{2}$$

$$H_2O + CH_4 \rightarrow CO + 3H_2 \tag{3}$$

Liquid Methanol is then created through methanol synthesis, letting syngas react with hydrogen to form methanol and water according to the following reaction [38]:

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \tag{4}$$

Zin et. al [36] discusses the environmental footprint depending on the methanol production pathway. They explain that methanol can be produced from captured CO_2 together with renewable hydrogen to achieve carbon neutrality. Renewable hydrogen can be produced through water electrolysis with electricity from only renewable resources such as wind or solar energy, and the CO_2 can be captured with the use of carbon capture [36]. Methanol produced from this process is called green methanol or e-methanol (e-MEOH). Su et.al [39] state that producing green methanol requires 1.045 times more electricity than conventional methanol. On the contrary, the traditional method of methanol production consumes 2.5 times as much thermal energy as the e-methanol. Thus, the total direct and indirect CO_2 emissions from green methanol are almost a third of the emissions from the conventional process. Because of this big gap between the various methanol production processes, this thesis will include both the conventional pathway, using NG-methanol and green methanol.

3.2 The Engine

Ship engines come in different variants. There are four-stroke engines or two-stroke engines. The Two-stroke engine has come to dominate the ocean-going shipping vessels. This mainly comes down to the increased efficiency of the slow-speed two-stroke engines. [10]

The engine used in all product systems is a 22.5 MW slow-speed, two-stroke direct drive engine from MAN. The engine model is called 7J80Me-C10.5 and can run on both heavy fuel oils, biofuels, and methanol. In reality, the engine looks different when running on methanol. Firstly, a specific coating in the cylinders is needed and secondly, a pilot fuel is needed to start the engine when running on methanol [40]. These differences are not taken into consideration in the product systems. This is because the differences are considered small and therefore have an insignificant impact on the LCA. The efficiency of the engine is assumed to be 50% throughout the entire thesis. The flue gas compositions produced in the engine depend on the fuel. The flue gases that will be considered in this report are the $SO_x, NOx_, N_2O$ PM, and CO_2 emissions.

3.3 Flue gas treatments

To reduce pollution from the engine, flue gas treatments can be used. Two commonly used technologies to minimize flue gas emissions are Selective catalytic reduction (SCR) and scrubbers. Both will be used in all the product systems in this study.

3.3.1 SCR

The most promising flue gas treatment to reduce NO_x emissions is an SCR system according to Ligang et al. [41] The NO_x emissions depend on combustion temperature, combustion time, and air-fuel ratio, but the NOx emissions will always be a trade-off with the CO_2 emissions. Therefore, in the MAN engine, all fuel types release allowed amounts of NO_x emissions at the cost of increased CO_2 emissions. [40] Because of that, all product systems will include an SCR system.

When flue gases from the engine enter the SCR an urea solution is sprayed on the flue gases. With flue gas temperatures above 200°C, the urea will decompose to form ammonia, which reacts with the NO_x to form nitrogen and water according to the chemical reactions below [41].

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O \tag{5}$$

$$2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O \tag{6}$$

Accordingly, ammonia works as a reducing agent, but to do so high temperatures are needed. Because of this, the SCR will be placed before the scrubber (as seen in figure 12) in order to maintain higher exhaust gas temperatures. The NO_x capture rate efficiency can reach above 95% [41]. Also, an ammonia slip can occur from an SCR because of an incomplete reaction between the urea and NO_x [42].

3.3.2 Scrubber

To reduce SO_x emissions wet scrubbers are most commonly used in the maritime sector. [43] For the VLSFO case, product system 1, a scrubber will therefore be used to remove the sulfur content, even if the sulfur content is already below the IMO regulations. This is because the SO_x levels should be put to a minimum before entering the CCS for optimal operation conditions [40]. In the biofuel and methanol cases, the scrubber will not operate since their flue gases do not contain any SO_x. There are different types of wet scrubbers; an open loop system, a closed loop system, or a hybrid between the both. In the open loop system sea water is sprayed on the flue gases after entering the scrubber. The SOx reacts with the water and forms sulfuric acid H_2SO_4 which is shown in the following chemical reaction [44]:

$$SO_2 + H_2O + \frac{1}{2}O_2 \rightarrow H_2SO_4 \tag{7}$$

The natural alkalinity of the seawater then neutralizes the sulfuric acid. The water is then discharged into the ocean. In a closed-looped scrubber system, fresh water combined with sodium hydroxide (NaOH) is used to neutralize the water. The chemical reactions are shown below:

$$NaOH + H_2SO_4 \rightarrow NaHSO_4 + H_2O 2NaOH + H_2SO_4 \rightarrow Na_2SO_4 + 2H_2O \tag{8}$$

The reactions result in the formation of sodium hydrogen sulphate ($NaHSO_4$) and sodium sulphate (NA_2SO_4) [44]. The closed-loop system is on the contrary recirculated in the system and only a small bleed-off occurs. For the hybrid case, the scrubber can operate in both closed and open mode. This might be useful for areas where the alkalinity in the seawater is too low and then the system can operate in a closed system mode. [43].

A closed-loop wet scrubber system will be used in this study, to enable routes at any sea, even where the natural alkalinity in the seawater is low. This type of scrubber can have a removal efficiency above 95%. The scrubber does not only remove SO_x emissions but also some PM. The PM2.5 removal rate is usually about 10% according to Yang et al. [43].

3.4 Carbon Capture

After the flue gases have been cleaned from SO_x, NO_x, and PM the flue gases enter an onboard carbon capture system with the purpose of capturing as much CO_2 as possible. There are several types of carbon capture technologies. The technologies can be divided into post and pre-combustion. The pre-combustion technology refers to capturing the CO_2 before combustion. Shortly, gasification is used to partially oxidize the feedstock and produce syngas. The syngas undergoes a water-gas shift reaction to increase the concentration of H_2 and CO_2, which is then captured from the gas mixture and the separated H-rich gas can be used as a clean fuel. [15] The advantage of the pre-combustion technology is that it reduces the gas volume which reduces the equipment investment. Furthermore, it allows higher CO_2 concentrations, which reduces the energy consumption.

The post-combustion working principle is instead based on capturing the CO_2 after combustion. The advantage of this technology is its ability to be retrofitted to already existing plants. Since the CCS in this study will be used on an already existing vessel the post-combustion technology will be best suited for this project. The post-combustion technology can be divided into four technology categories; absorption, adsorption, membranes, and cryogenics. The most dominant technology in the field is absorption technology. [15]. This technology is also considered most suitable for this study since many other case studies have been performed on this technology for onboard use [12] [1] [15]. In all these case studies the used absorbent has been amine. Thus, the amine-based post-combustion technology will be chosen for this case study.

The absorption carbon capture system is seen in Figure 17. It contains two main components; an absorber and a desorber. The solvent used in the system is a 30 wt% monoethanolamine (MEA) solution which is the most common amine used for this technology [12] [1] [15].

Before, the upstream exhaust gases enter the absorber the gases need to be cooled in a cooler since the MEA solvent is more favorable with lower temperatures. When the cooled gases enter the absorber the CO_2 is absorbed in the lean MEA solvent. [12] This reaction is as follows [45]:

$$CO_2 + HOCH_2CH_2NH_2 \rightarrow HOCH_2CH_2NHCOO^- + H^+ \tag{9}$$

The reaction shows that MEA ($HOCH_2CH_2NH_2$) reacts with CO_2 to produce a carbamate ion ($HOCH_2CH_2NHCOO^-$) and a proton. On top of the absorber, a water washing section is placed, to minimize amine losses before the clean gas is vented. The CO_2 rich

MEA solvent exiting the base of the absorber traverses a lean-rich heat exchanger before proceeding into the stripper. Afterward, the CO_2 is desorbed by the heat input from a reboiler. The chemical reaction is the reversed reaction shown in Equation 9. Furthermore, the CO_2 is extracted from the upper section of the stripper, whereas the revitalized, heated solvent from the lower section of the stripper flows through the lean-rich heat exchanger before returning to the absorber for recirculation. [12] To compress and liquify the CO_2 a compressor and a condenser is needed [13]. Finally, the liquefied CO_2 will be stored in an onboard tank on the vessel.

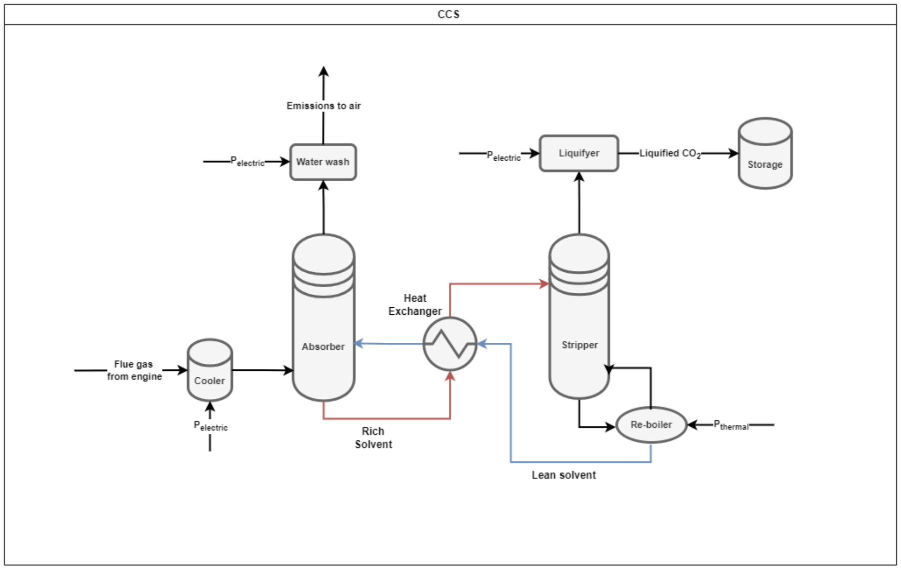


Figure 17: Design of the Onboard Carbon Capture

Worth noticing is that pumps is not shown in figure 17, since they do not play a major role in the systems energy consumption and therefore do not play a major role in the LCA. The water in the water wash is also neglected since there is no wastewater and the mass balance is obtained during the operation phase. [46] The major energy consumed in the CCS is due to the reboiler, called reboiler duty. This energy is waste heat taken from the engine and afterburner.

3.5 Afterburner

If the thermal waste heat from the engine is not enough to cover the CCS reboiler duty, an afterburner can be used to boost the thermal energy. An afterburner is an additional combustion component, where additional fuel is combusted together with air and mixed with the flue gases from the engine. [16]. The boiler duty and the additional fuel consumption will be calculated in Chapter 4.1.3.

3.6 Carbon Storage

When the CO_2 has been captured and liquefied the carbon can either be sold and used as a feedstock, called carbon capture and usage (CCU), or permanently stored in the ground, called carbon capture and storage (CCS). [47]

CCU is a term to describe all scenarios when the CO_2 is used in another process as a feedstock. The CO_2 utilization pathways are numerous with the main ones being the chemical industry and agriculture. Some processes directly relating to this thesis are in the production of both Urea (used in the SCR) and Methanol. [48] Calculating the impact from CCU can be challenging as allocation issues can occur depending on the system boundaries as mentioned and exemplified in chapter 4.3.1.

A promising method of storing CO_2 permanently is using deep unmineable coal seams through adsorption. Adsorption refers to the adherence of gas molecules to the surface of a solid material. In this context CO_2 molecules adhere to the surface of coal seams, effectively trapping them underground [47]. Another option is dissolution in so-called saline aquifers, which is defined as porous and permeable reservoir rocks that contain saline fluid in the pore spaces between the rock grains. Sequestration in saline aquifers relies on three mechanisms: trapping of CO_2, dissolution, and finally formation of minerals in the pore spaces. [49] A current example of storage in deep saline aquifers is the Sleipner project in Norway that sequesters CO_2 from CO_2 reduction of oil. [50]

In this study, the CO_2 will be transported to a harbor and permanently stored in the ground. This decision was made for two reasons. Firstly, treating the CO_2 as a feedstock will imply that LCA will receive two useful outputs, which leads to an allocation problem. Secondly, storing the CO_2 in the ground will be the only way of receiving negative CO_2 emissions [22], and therefore the most efficient way of achieving IMOs 2050 CO_2 reduction goal.

Permanent CO_2 storage is a possibility for the future but lacks commercial maturity as of 2024. Therefore few actual measurements can be found and no large-scale example of commercial facilities can be used. This report will therefore consider planned projects as the basis for permanent storage. Several projects exist and one of the projects, closest to realization is the Northern Lights project in Norway. A project with the capacity to store 1.5 Mt CO_2/year. [51] The Northern Lights project aims to be a part of a larger CO_2 sequestration network in Europe and will require liquid CO_2 to be delivered to the harbor from industrial sites.

4 Applied Methodology

The applied methodology is divided into two parts; System Modeling and the LCA Procedure. The main method used in the report is an LCA, but to be able to apply it some parts of the product systems had to be modeled. Firstly, the required models will be explained, and afterward, the LCA process for this study will be described.

4.1 System Modeling

4.1.1 Modeling of the Systems Energy Consumption

To apply an LCA the energy flows through the product systems had to be calculated. Thus, the first model was set up to calculate the energy consumption of each process in the systems. The simplified model is shown in Figure 18. Chemical energy enters the engine and afterburner as fuel, called $E_{C,fuel}$. The engine converts chemical energy to mechanical work, E_M that goes into the shaft $E_{M,shaft}$ and the generator. The thermal energy is divided into useful thermal energy, called waste heat return unit $E_{T,WHRU}$, and thermal losses $E_{L,engine}$. Furthermore, the generator converts the mechanical energy to electric energy, $E_{E,generator}$, and some losses $E_{L,generator}$.

Furthermore, the chemical energy from the fuel also enters the afterburner, which converts the chemical energy into thermal energy $E_{T,afterburner}$ and some losses $E_{L,afterburner}$. These depend on the afterburner efficiency.

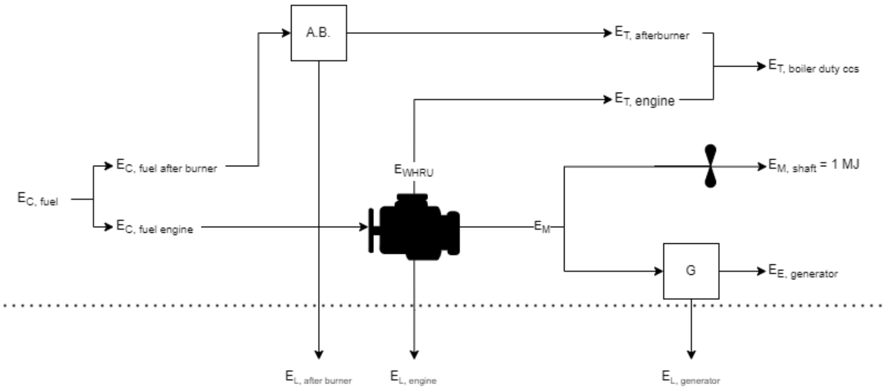


Figure 18: Energy Consumption for each Process

The useful energy from the engine was assumed to be all the mechanical work. Therefore, the engine efficiency includes both $E_{M,shaft}$ and $E_{E,generator}$. The expression of the engine efficiency and the waste heat return unit efficiency is therefore as follows:

$$\eta_{engine} = \frac{E_{M,shaft} + E_{E,generator}}{E_{C,fuel}} \tag{10}$$

$$\eta_{WHRU} = \frac{E_{WHRU}}{E_{C,fuel}} \tag{11}$$

Likewise, the efficiencies for the generator and the afterburner could set up as follows:

$$\eta_{generator} = \frac{E_{E,generator}}{E_M - E_{M,shaft}} \tag{12}$$

$$\eta_{afterburner} = \frac{E_{T,afterburner}}{E_{C,fuelafterburner}} \tag{13}$$

The efficiencies calculated were used in the software to receive the correct process flows.

4.1.2 Modeling of Flue Gases

When setting up the complete LCA product systems some simplifications were done compared to the reality. One of these are simplifications regarding the flow of flue gases. In figure 19 two models are shown. The left one is a representation of reality, where after combustion, the flue gases enter each flue gas treatment component after each other. All flue gases first enter the SCR, where most of the NO_x is removed. The remaining gasses then enter the scrubber where most SO_x and some PM are removed. Lastly, the remaining flue gases enter the CCS. In other words, all the flue gas treatment components need to handle more than one type of flue gas. Instead, in the right model, only the gases that are mainly treated in the component are assumed to enter the component. Only SO_x and PM are assumed to enter the scrubber, NO_x the SCR, and CO_2 the CCS. This simplification was made to avoid problems in handling multiple gases in the component. For example, in reality, not only CO_2 enter the CCS, but how the leftover SO_x and NO_x affect the CCS is complex and difficult to handle.

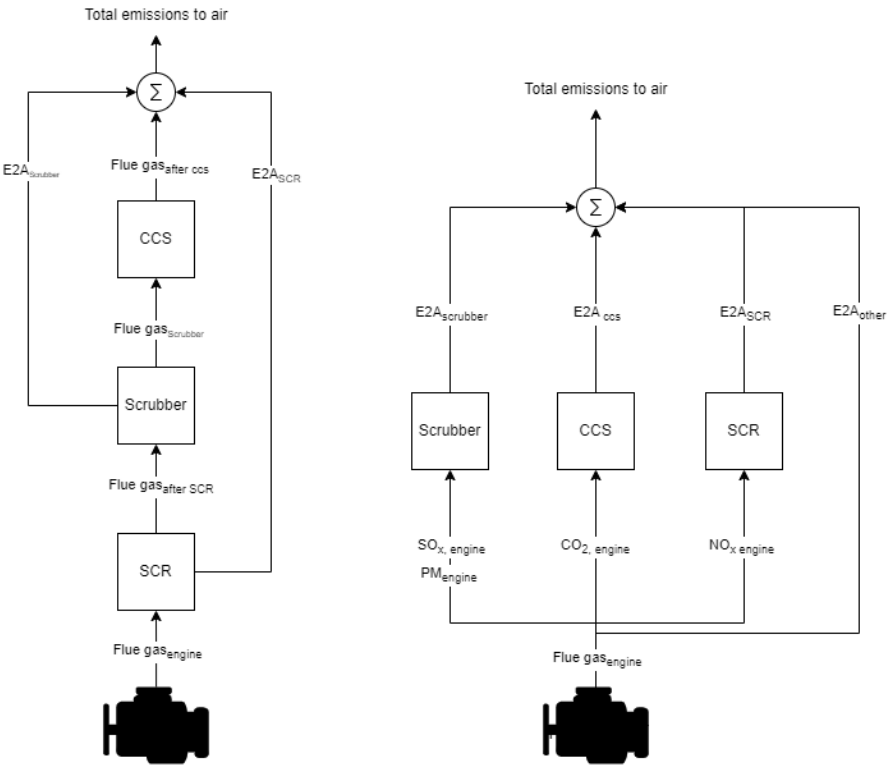


Figure 19: Real (left) and simplified (right) model of the flue gas treatments, where E2A stands for emissions to air.

4.1.3 Modeling of Onboard Carbon Capture

The CCS is a complex component with many flows and parameters that can be calculated. Therefore, it was modeled in a way that each parameter had a meaningful impact on the result obtained in the LCIA without making the computations and data collection unnecessarily complex. This was especially important during the operation phase of the onboard carbon capture system as several flows occur, but only some flows contribute to energy consumption, increased emissions, and material usage.

To model the impact of the CCS during operation, a selection of in-and-out parameters was used. This selection was based on previous studies [1] [52] [16]. The majority of data and parameters in Table 1below were taken from research studies on carbon capture aboard shipping vessels to ensure capability with the rest of the ship's systems while some data points had to be derived from research focusing on other point-carbon capture facilities. All parameters were linearly scaled and normalized to the same unit to analyze the deviation among the different systems and try to identify key parameters that had to be included in a later sensitivity analysis. The parameters as in- and outputs from the CCS are outlined in Table 1.

Table 1: Process table for the operation phase of CCS with functional unit = $1/tCO_2$

Inputs to OCCS		
Parameter	Symbol	Unit
Thermal energy (boiler duty)	E_{th}	GJ/tCO_2
Electrical energy	E_e	GJ/tCO_2
Flue gas feed flow	$F_{Fluegas}$	kg/tCO_2
MEA feed flow	F_{MEA}	kg/tCO_2
NaOH	F_{NaOH}	$kg/tCO2$

Output from OCCS		
Parameter	Symbol	Unit
Captured CO_2	$CO_{2_{captured}}$	tCO_2/tCO_2
Emissions to Air	$E2A_X$	kg/tCO_2

The specific values of each parameter are shown in Table 3 and were taken directly from the literature. However, the value for the parameter *Thermal Energy* could not be taken directly from the literature but had to be computed to find a value. The thermal energy requirement of the CCS is primarily the thermal energy needed to heat the amine-CO_2 mixture in the stripper to make the CO_2 release from the amine. The so-called re-boiler duty is therefore the key point of interest when it comes to deciding the magnitude of E_{th}. The literature is not entirely concise in how much thermal energy needs to be added per ton CO_2 captured. Determining the thermal energy usually requires advanced calculation on a case-to-case basis. [53] Determining the exact figure is not within the scope of this study but ensuring the correct components are included. Previous studies on CCS are conflicted if the thermal energy from the engine is enough to reach a capture rate above 50%. [52] [16]. It was therefore needed to estimate the thermal energy required to determine if the thermal energy from the engine alone was sufficient to power the reboiler or if an afterburner was needed. $E_{th,boiler}$ was estimated using the surrogate model presented by W.Chung and J.H.Lee [53] to calculate the re-boiler duty within $+/-5\%$ for a generic amine-based carbon capture unit. In the surrogate model, the following parameters were needed to estimate the boiler duty, $E_{th,boiler}$:

$$P_{FEED} = pressure\,of\,flue\,gas \tag{14}$$
$$x_{CO_2} = molfraction\,of\,CO_2 \tag{15}$$
$$r_{CAP} = capture\,rate \tag{16}$$
$$P^{eff}_{CO_2} = P_{FEED} \cdot x_{CO_2}(1 - r^{\beta}_{CAP}) \tag{17}$$
$$E_{th,boiler} = \alpha ln P^{eff}_{CO_2} + f_{stm,0} \tag{18}$$

The values of the flue gas pressure and the CO_2 mole fraction were obtained from MAN, while the parameters α, β and $f_{stm,0}$ were given from the study by W.Chung and J.H.Lee [53]. Moreover, the capture rate is set to 70% since this is a capture rate used in previous studies [1] [52]. With these parameters the boiler duty $E_{th,boiler}$ was estimated for the various product systems.

Additionally, the need for an afterburner could be calculated. According to the previous model in figure 18 the additional thermal energy from an afterburner was calculated from the following relations:

$$E_{T,afterburner} = E_{T,boilerduty} - E_{T,engine} \tag{19}$$
$$E_{T,engine} = \frac{q \cdot (1 - \eta_{engine}) \cdot \eta_{WHRU}}{x_C \cdot C_{toCO2}} \tag{20}$$

Where q is the heating value of the fuel,(see table 2) x_C is the carbon content in the fuel and C_{toCO2} is the mole fraction of carbon that turns into CO_2 during combustion. The latter values are 0.86 (for VLSFO) and 3.67 respectively according to [54], [55]. The complete calculations are provided in Appendix 8.

Knowing these equations and parameters the additional energy from an afterburner was computed for all product systems. The calculated values were positive, and therefore it was stated that an afterburner was required for the systems.

Table 2: Parameters used to compute the boiler duty for each product system

Fuel	Heating value [MJ/kg]	wt% C in fuel	mol% CO_2 in flue gas
VLSO	41.1 [40]	85 [55]	5.2 [56]
Biofuel, UCO	37 [40]	77 [40]	5.2 [56]
Biofuel, Soy/Rapeseed/Palm	37.4 [40]	78 [40]	5.2 [56]
Methanol	19.9 [40]	62 [8]	11.1 [8]

4.2 Software Modeling

To perform the LCA several product systems had to be set up. The calculation of the total flow amounts, LCIA results, and other aspects relating to the modeling was done using an LCA software. There are several large software available for LCA; GaBi, SimaPro, oneClickLCA, GREET RnD, etc. All of the software have different niches and approaches that make them suitable for different purposes. This project was conducted with the help of an open-source software called OpenLCA. The choice of software might impact the outcome and should be considered when reviewing the final results [57].

OpenLCA is the only free open-source LCA software suitable for professional use and was therefore chosen in this study. It is developed by the company GreenDelta and allows for easy implementation of databases, flexible editing of process flows, and iterative development of the model.

The modeling of the product systems in openLCA takes place over several levels, which are visualized in Figure 20. The lowest level is the flow. The flows have three subcategories; elementary flows (green), product flows (blue), and waste flows (orange). The elementary flows are flows to or from the environment, the product flow is a flow inside the product system and waste flows are flows that are unwanted by-products. The flows are modeled as input and outputs in what is called a process (pink border). A process is considered a *black-box* with a certain amount of input flows and a certain amount of output flows. The process requires a reference flow to which all other inputs and outputs are related (e.g. flow amount [kg/kg reference flow]), which is the bold flow in Figure 20. The processes are lastly connected to other processes to create an entire product system.

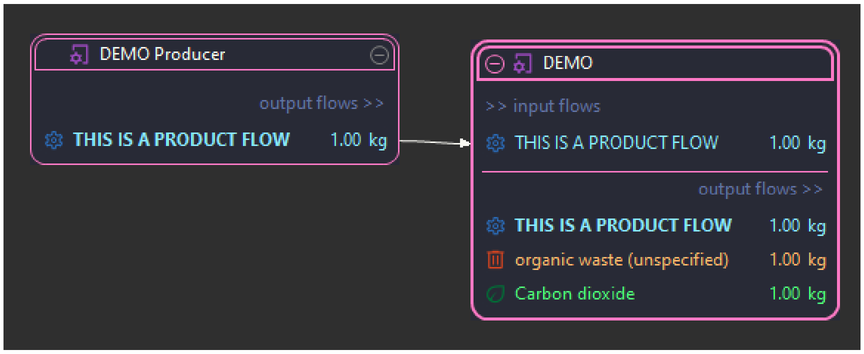


Figure 20: Elements used to model in OpenLCA

These product systems are used to determine the total elementary flows to the environment to assess the impact of the product system. Each elementary flow is characterized by what is called a characterization factor. This factor is used to convert an elementary flow to an impact equivalent. Example: 1 kg Methane to 25 kg/CO_2eq to determine the global warming impact from that elementary flow.

4.3 Life Cycle Assessment Procedure

To answer the research question of this thesis, an LCA has been applied to the product systems analyzed. In this section, the entire LCA process will be described. Firstly, the scope will be described, then the life cycle inventory process, and last the life cycle impact assessment.

4.3.1 Scope

In this section, all parts that have to be included in the scope according to ISO 14044 will be discussed.

Functional Unit The functional unit for this study was chosen to be 1 MJ on the shaft. This means that the useful output of the product systems is work on the shaft. All other processes in the product system were therefore normalized to this value.

Geografical Area The market share of MAN's low-speed diesel engines is 80% counting by installed power. [58] This means that MAN's engines can be found all around the world. Therefore, to simplify and limit the scope of this thesis the theoretical ship in this thesis was assumed to travel between Rotterdam harbor and the harbor in Los Angeles. These harbors were chosen since they are the largest ones in Europe and North America [59], [60].

Time Horizon This thesis aims to assess emissions related to the IMO 2050 goal and thus 2050 was the shortest time horizon applicable. However, regarding the effects of climate change, a 100-year perspective was used, meaning GWP100 was adopted.

System Boundaries The system boundary applied in the study is shown in Figure 21. It shows that this study focused on the ship's fuel pathways and operation phase. Neither the ship's manufacturing nor the ship's end-of-life treatment was included. This was not included since the ship was assumed to have already been built. The study's goal was to find the best innovation for an already existing ship and since the ship looks the same for all systems, manufacturing, and end-of-life are not considered. The CCS manufacturing phase was not included either even if it did not already exist on the ship. This was mainly because there was not enough time to include the manufacturing of the CCS within the time frame of this study. Moreover, other consumables for the operation phase were not included. This could cover oils for the engine etc. This was not included since these are considered minor compared to fuel consumption, so the effect was considered negligible.

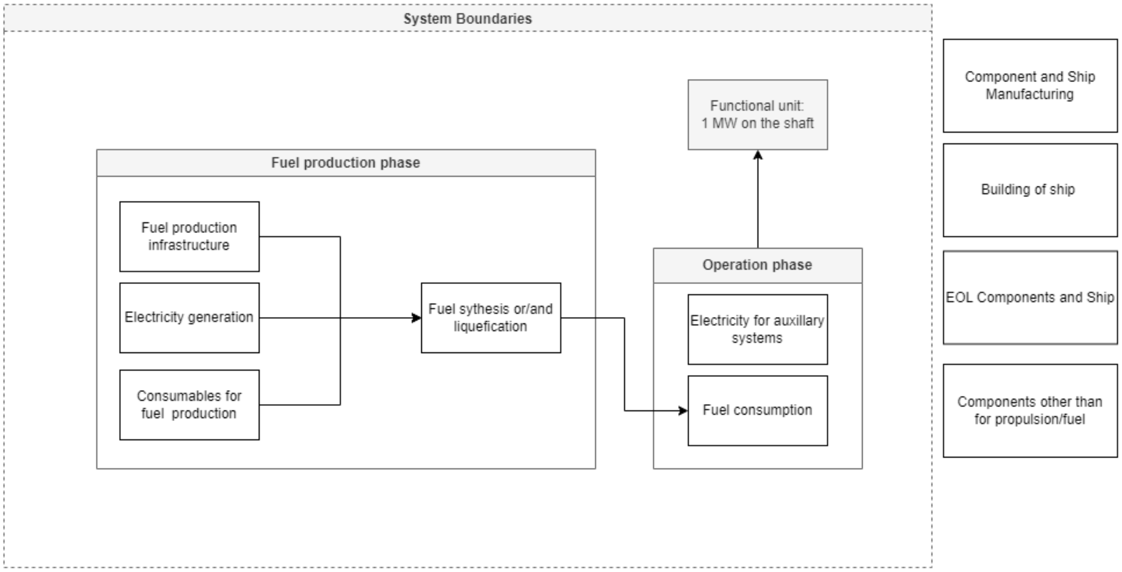


Figure 21: The system boundaries for this report

Cut-off criteria The project had to include as much of the required data as possible. Due to limitations in available data, a cut-off criterion was set: All processes needed to have 95% of the mass represented and 95% of the energy. No single flow greater than 1% of the total mass or energy could be omitted from the LCI. This cut-off criteria were suggested by ISO 14044 [18] and therefore chosen in this thesis.

Data requirements and data quality requirements The project only considered emission data from published articles, established databases, or government institutions, with the exception of some manufacturing data. The time perspectives for each data point were different. The emissions and chemical compositions of HFO had to be from after 2020 due to IMO regulations. The production of different biofuels and methanol fuels was as recent as possible but no strict limit was set. The data for the operation of the CCS also had to be as recent as possible and studies using CCS in a maritime context or together with an ICE were used when possible. When feasible, all geographically significant data was taken from the EU or the US.

Allocation Allocation was only necessary during the production of each fuel. Each source specifies the allocation method. GREET, which was the most used database in this study utilizes mass allocation. Regarding biofuels, GREET employs different accounting methods based on the origin of carbon sources: biogenic carbon emissions are considered carbon-neutral, while biogenic carbon sequestration is seen as negative carbon emissions. Also, sequestration carbon for methanol production is seen as negative. On the other hand, fossil carbon emissions are considered as positive carbon emissions, while fossil carbon sequestration is seen as carbon-neutral. [61] These numbers taken from GREET were well-to-pump perspective meaning only the burdens from production and transportation to pump are taken into account. Fuels capturing CO_2 can therefore have a net negative value before combustion. By expanding to a well-to-wake perspective the captured CO_2 were released to the air and therefore not net negative anymore. (See Chapter 2.4 for more on allocation)

Comparisons between systems It was possible to compare the systems as all the systems have the same functional unit and similar pathways except for the magnitude of some values and the fuel production.

Critical review This study was reviewed by professors at Lund University and a student opponent during the final presentation of the Thesis.

4.4 Life Cycle Inventory

In this section, the life cycle inventory will be presented. First, all process flows for the product systems are shown and after that, the data inventory is presented.

4.4.1 Product System Processes and Flow

The product systems were simplified into unit processes as seen in Figure 22.

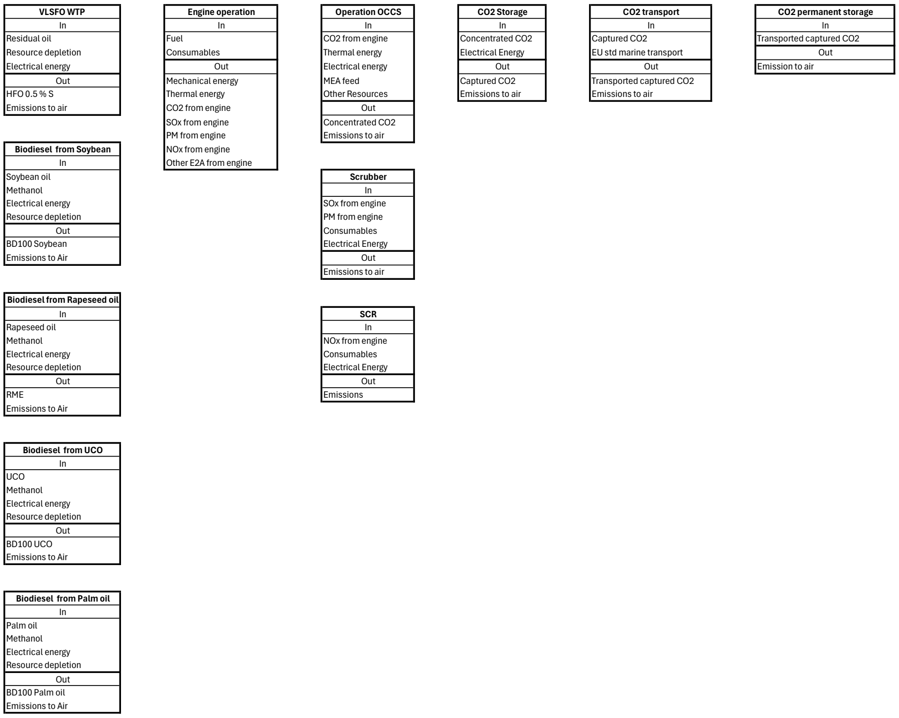


Figure 22: Overview of the significant processes that make up the product systems

The process flows of the product systems were modeled in the software openLCA, which is shown in Figure 23. This figure shows the entire product system of the VLSFO case. All seven product systems were built with the same layout but with different values depending on the fuel. All product systems can be found in the Appendix.

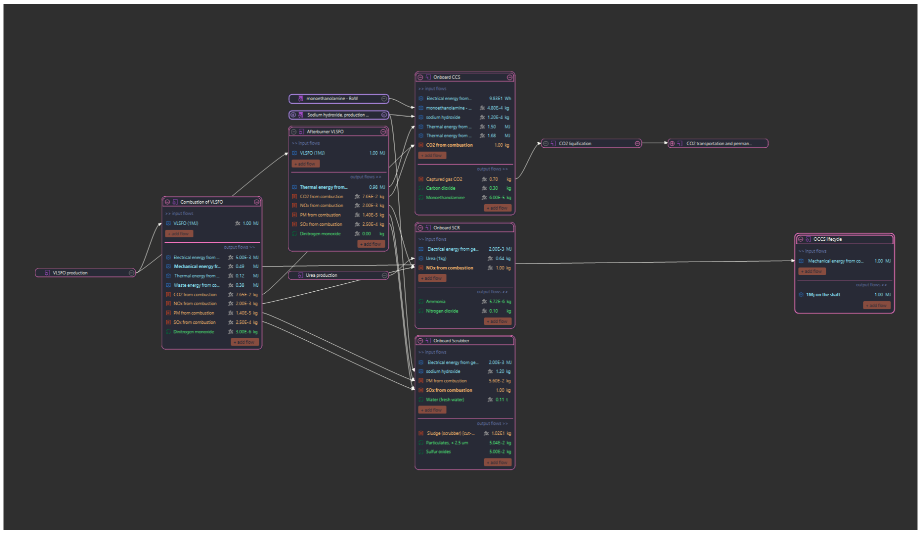


Figure 23: Process Diagram as modeled in OpenLCA. (NOTE! The values are not necessarily the ones used as specific values are changed before the calculation of the LCIA)

The first process in the product systems is the production of the fuels. The production data is mostly taken from GREET and ProBas. Which fuel is taken from which database is shown in Table 4. The produced fuel flows into the engine called *consumption of fuel*, and the *afterburner*. The engine has mechanical energy to the shaft as a reference flow, whilst the afterburner has thermal energy as a reference flow. From the *combustion of fuel* process, flue gases enter the *SCR*, *scrubber*, and *OCCS* separately. The flue gases which is not captured are released into the air. These processes also consume some substances; the SCR consumes urea, the scrubber NaOH, and the CCS consumes MEA. The production of these consumables are included in the model, and their data points are taken from various sources listed in Table 4. There is a product flow from the *OCCS* called *liquefication*, which includes cooling and compression of the CO_2. This process has liquefied CO_2 as a useful output. This flow goes into the process *Transportation and storage* which transports the liquefied CO_2 and stores it permanently in the ground.

The last process in the product system is called *OCCS Lifecycle*. The only purpose of this process is to clarify the functional unit. The process says that the mechanical work from the engine is used on the shaft, which is the functional unit of the entire product system.

4.4.2 Data Inventory

To model the product systems in openLCA several data points were collected. All the data used in the LCA is listed in table 3. In this section, some of the assumptions and decisions made concerning the data points will be explainedd.

Table 3: Data Collection summary with Values and Sources

Component	Parameter	Value	Unit	Reference
Engine	η_{Engine}	50	%	MAN
	η_{WHRU}	25	%	Estimation, MAN
Flue gas	CO_2 concentration	-	g/MJ_{shaft}	MAN
	NO_x concentration	-	g/MJ_{shaft}	MAN
	SO_x concentration	-	g/MJ_{shaft}	MAN
	PM concentration	-	g/MJ_{shaft}	MAN
Afterburner	$\eta_{Afterburner}$	85-95	%	[62]
SCR	Urea consumption	1.6	$kg/kgNOx_{in}$	MAN
	Electricity consumption	0.039	$MJ/kgNOx_{in}$	[63]
	NOx removal rate	95	%	
	Ammonia slip	$5,72 \cdot 10^{-6}$	$kg/kgNOx_{in}$	[42]
Scrubber	Freshwater consumption	111	kg/SOx_{in}	[64]
	Electricity demand	0.157	$MJ/kgSOx_{in}$	[65]

Table 3: Data Collection summary with Values and Sources

Component	Parameter	Value	Unit	Reference
	NaOH consumption	0.0012	kg/MJ_{shaft}	MAN
	SOX removal rate	95	%	[43]
	PM removal rate	10	%	[43]
CCS	Boiler Duty	Calcuated value	MJ	[53]
	Electricity consumption	98.3	Wh/$kgCO_{2in}$	[1]
	MEA consumption	1.6	$kg/tCO2_{in}$	[66]
	NaOH consumption	0.12	$kg/tCO2_{in}$	[1]
	Activated Carbon	0.07	$kg/tCO2_{in}$	[1]
	Freshwater consumption	18.1	$kg/tCO2_{in}$	[1]
	Capture rate	70	%	[1]
	MEA, emissions to air	0.06	$kg/tCO2_{in}$	[1]
	Ammonia, emissions to air	0.03	$kg/tCO2_{in}$	[1]
Liquefier	Electric consumption chiller	0.0645	kWh/kg CO2	[1]

Table 3: Data Collection summary with Values and Sources

Component	Parameter	Value	Unit	Reference
	Electric consumption compressor	0.1	kWh/kg CO2	[67]
	CO_2, emissions to air	1	% of boil of gas	[1]
Transportation	Transportation by ship	0.752	t*km	ProBas
Permanent storage	CO_2, emissions to air	0.5	% of stored CO_2	[68]

Urea The urea consumption is a water solution with 40 wt% urea. [40]

Electricity consumption The fuel cost from electricity consumption of the SCR, scrubber, and CCS was included in the initial assessment of this thesis. However, it was assumed that the generator onboard produces enough electricity without additional fuel consumption. In reality, a generator would require more mechanical energy which in turn would require an increase in fuel consumption for the same energy on the shaft. This value is estimated to be between 2 - 19 % depending on the study [15] [1]. There was also an option to use external generators fueled by e.g. diesel thus requiring another fuel in the model. To simplify the product systems the generator was therefore not included. Instead, an increase in energy requirement was included in the sensitivity analysis to assess the assumption to omit the fuel consumption from electricity production. This is equivalent to reducing the engine efficiency to match the energy required to power the generator.

Capture rate The capture rate of the CCS in this study was set to 70%. Since this study uses an afterburner it will be possible to boost the thermal energy enough to reach a capture rate above 50% according to Einbu et. al [16]. In the study made by Juyoung et. al [12] a capture rate of 90 % is used, while Kanchirallan et. al [1] uses a capture rate of

70% in their study. Accordingly, values between 50% and 90% capture rate can be found in previous studies. Therefore a mean capture rate of 70 % was used in this study.

MEA consumption The MEA consumption is a water solution with 30 wt% MEA. Even if MEA is reused in the CCS a MEA consumption is required because of MEA degradation. This occurs because of irreversible reactions between the amine and residual products from the flue gas pre-treatment, like $SO_x and NO_x$ [69] To minimize the content of SO_x and NO_x an SCR and scrubber is therefore of utmost importance. As mentioned the flue gases were modeled in a way so that the CCS only has CO_2 as a flue gas input. This was made for simplicity in modeling. MEA degradation was still taken into consideration.

Transportation The captured, liquefied CO_2 was assumed to be transported by sea at a distance of 725 km. This represents the distance between Rotterdam harbor and the harbor in Stavanger, close to the Northern Lights project in Norway, where the CO_2 is assumed to be stored. [51]

Permanent storage The emissions associated with the permanent storage are based on the environmental permission for the Northern Light project. [68] No other emissions associated with the permanent storage could be found and none could be provided by institutions such as the Norwegian Offshore Directorate when inquiring. There are likely other emissions associated with storing CO_2 permanently.

4.4.3 Databases

The databases used in this thesis were GREET, ProBas, ELCD, and Ecoinvent. What dataset is used for each fuel and consumable is shown in Figure4. Briefly, this section will provide some information about each database.

GREET GREET stands for Greenhouse Gases Regulated Emissions and Energy Use in Technologies and was developed by Argonne National Laboratory with support from the U.S Department of Energy [61]. All data is therefore based on the US market. GREET was developed to serve as a guide for decision-making, research, development, and regulatory measures in the transportation and energy sector. It mainly includes fuels and consumables. [70] This database was chosen because it was the only database including HFO with a sulfur content of 0.5% found.

ProBas ProBas is a database that was directly downloaded to openLCA for free, through their webpage called *openLCA Nexus*. It is a German database developed by the German

Federal Environment Agency. It includes units and combined processes for energy, materials, products transportation services, and waste. [71] The database was chosen since it included the data needed and was easy to implement into the software.

ELCD ELCD stands for European Life Cycle Database and was also directly downloaded to the software through *openLCA Nexus* for free. This database is developed from EU-level business associations by Green Delta. The dataset includes materials, energy carriers, transport, and waste management. [72] The database was chosen since it is a broad EU-based database, which was easy to implement in the software and contained key values not found in GREET or ProBas.

Ecoinvent EcoInvent is a non-profit organization based in Zurich Switzerland, which is committed to providing high-quality data for environmental assessments over the world. [73] The dataset was accessed through a University license. It is worth noticing that the license was only available for an old version of Ecoinvent from 2015. Thus, the database is only chosen for processes that could not be found in the other databases.

Table 4: Production of consumables and where the data comes from

Consumable	Upstream Emissions Source
VLSFO	GREET
BD palm oil	ProBas
BD rapeseed oil	ProBas
BD soybean	GREET
Biofuel UCO	GREET
E-methanol	GREET
Methanol NG	GREET
Urea	GREET
NaOH	ELCD
MEA	Ecoinvent 3.2

4.5 Life Cycle Impact Assessment

Lastly, the third phase, LCIA, will be presented, in this chapter.

4.5.1 LCIA Method and Impact Categories

When choosing the LCIA method it was found that no single LCIA method is standard for marine fuel analysis, which can be seen in Table 5. Instead, the project's goal and geographical scope worked as an indicator of what LCIA method is best suited. This project aims to analyze which fuel together with CCS can decrease CO_2 emissions the most, therefore using only midpoint impact categories suits well enough. Based on the data collected during the LCI, the preferred method is either ReCiPe 2016 or EF 3.0 as both contain lots of data for the elementary flows with characterization factors as GWP100. ReCiPe 2016 is an LCIA method developed by a collaboration between three universities and one institution. It can be used for several geographical areas while EF 3.0 is developed by the EU and is primarily intended to be used with the EU as the geographical scope. ReCiPe and CML-IA share similarities as ReCiPe is a development of an early CML version. The two methods can however indicate different impacts so a critical analysis of all LCIA results, no matter the method, is needed to draw correct conclusions. This project will use ReCiPe 2016 as the LCIA method of choice due to the extensive number of midpoint categories and no restrictions in geographical areas.

Table 5: LCIA methods used in other research

Method	Subject / Scope	Source
ReCiPe 2008	Alternative marine fuels (WTW)	[74]
EF 3.0	Alternative marine propulsion (CTG)	[1]
IPCC	Alternative marine fuels (WTW)	[27]
CML	Alternative marine fuels (WTP)	[11]
ReCiPe 2016	Alternative marine fuels (WTW)	Internal document at MAN

Table 6 shows all impact categories considered in ReCiPe.

Table 6: Impact Categories ReCiPe 2016

Midpoint Categories	
Category	Unit
Particulate matter	kgPM2.5 eq
Trop. ozone formation	kgNOx eq
Ionizing radiation	kBq CO-60 eq
Stratos. ozone depletion	kgCFC11 eq
Human toxicity (cancer)	kg1.4-DCB
Human toxicity (non-cancer)	kg1.4-DCB
Global warming	kgCO2 eq
Water use	m3
Freshwater ecotoxicity	kg1.4-DCB
Freshwater eutrophication	kgP eq
Trop. ozone (eco)	kgNOx eq
Terrestrial ecotoxicity	kg1.4-DCB
Terrestrial acidification	kgSO2 eq
Land use/transformation	m2a crop eq
Marine ecotoxicity	kg1.4-DCB
Mineral resources	kgCu eq
Fossil resources	kg oil eq

4.5.2 Sensitivity Analysis

The model is a parameterized model with the function to calculate the well-to-wake emissions for a propulsion system connected to a carbon capture unit. To do this, an LCA was conducted using data from several sources. Thus, a rigorous analysis regarding the models' parameters was needed to determine if some factors are dominant, behave unexpectedly, or otherwise need further studying or checking.

A way to do this was to conduct a sensitivity analysis of the values. There are several methods to do this but the one-at-a-time (OAT) approach was utilized in this report. OAT works by changing one parameter individually and assessing if the response to the final result is proportionally affected by the change compared to a base case. The OAT approach can also allow for the inclusion of parameters that were assumed to not be important to the result like the electricity load in this report.

4.5.3 Monte Carlo Simulation

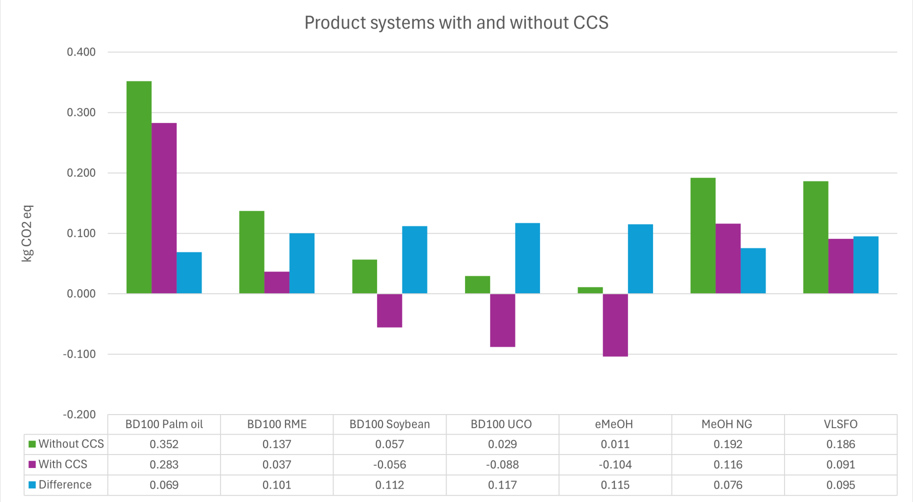
To investigate irregular behavior in the model further, a Monte Carlo simulation was conducted. The Monte Carlo simulation is also referred to as the gambling approach and was used to determine how random changes in the data affect the spread of results. Each included parameter was assigned an uncertainty distribution, e.g. normal distribution with a standard deviation of +/- 10%. The Monte Carlo simulation was then randomized to each parameter according to the set distribution several times to asses the total mean and distribution from all the iterations. The final result from the Monte Carlo assessment gives the most accurate uncertainty measurement of the model by including cascading errors that can propagate over several linked unit processes [75].

5 Results

In this section, the results from the LCA will be presented.

5.1 Global Warming Potential

The global warming potential of each fuel type is shown in Figure 24. If looking without capture of CO_2 from the CCS (green columns), it can be stated that system 2.a) has the highest global warming potential of 0.352 kg CO_2 eq, followed by system 3.b) methanol from NG with 0.192 kg CO_2 equivalents. System 1, VLSFO, has a GWP of 0.186 kg CO_2 eq. The fuel with the lowest GWP is system 3.a) green methanol with only 0.011 kg CO_2 eq, followed by system 2.d)BD100 UCO, system 2.c) BD100 Soybean and system 2.b)BD100 RME, with respectively 0.029, 0.057, and 0.137 kg CO_2 eq.



	BD100 Palm oil	BD100 RME	BD100 Soybean	BD100 UCO	eMeOH	MeOH NG	VLSFO
🟩 Without CCS	0.352	0.137	0.057	0.029	0.011	0.192	0.186
🟪 With CCS	0.283	0.037	-0.056	-0.088	-0.104	0.116	0.091
🟦 Difference	0.069	0.101	0.112	0.117	0.115	0.076	0.095

Figure 24: GWP of each product system. The green column shows results without the impact of CCS, purple with the impact of CCS, and blue the difference between the two cases.

The global warming potential with the effects of the installed CCS is also shown in Figure 24. The provided figure shows that system 2.a) with palm oil still has the highest GWP with a value of 0.283 kg CO_2 eq, followed by system 3.b) methanol from natural gas with 0.116 kg CO_2 eq, system 1, VLSFO with 0.091kg CO_2 eq and system 2.b)BD100 RME with 0.037 CO_2 eq. These product systems result in positive GWP values. On the contrary, system 2.c)BD100 Soybean, system 2.d)BD100 UCO, and system 3.a)Green methanol all receive negative values of the GWP. Each value is respectively -0.056, -0.088, and -0.104kg

CO_2 eq.

Table 7 shows the additional fuel consumption and energy consumption when operating the CCS.

Table 7: The increase in energy and fuel when using the CCS

	No CCS	BD100 Palm oil	BD100 RME	BD100 Soy	BD100 UCO	Green MeOH	NG MeOH	VLSFO
Fuel Energy consumption [MJ]	2	2.245	2.245	2.245	2.252	2.271	2.271	2.249
Fuel mass consumption [kg]	-	0.060	0.060	0.0600	0.061	0.114	0.114	0.055
Increase in fuel consumption [%]	0.00%	12.26%	12.26%	12.26%	12.62%	13.55%	13.55%	12.45%

5.2 Biodiesel, With and Without Uptake of CO_2

To show the difference between various accounting methods for biofuels, an example is presented for BD100 Soybean in Figure 25. The graph shows how the results differ depending on how biodiesel is accounted for. The CO_2 emissions can either be seen as neutral, because of the uptake of CO_2 or not. Both cases of with and without uptake of CO_2 are shown in figure 25. The same results but with the effect of CCS are also shown in the graph. The standard accounting method is to include CO_2 uptake.

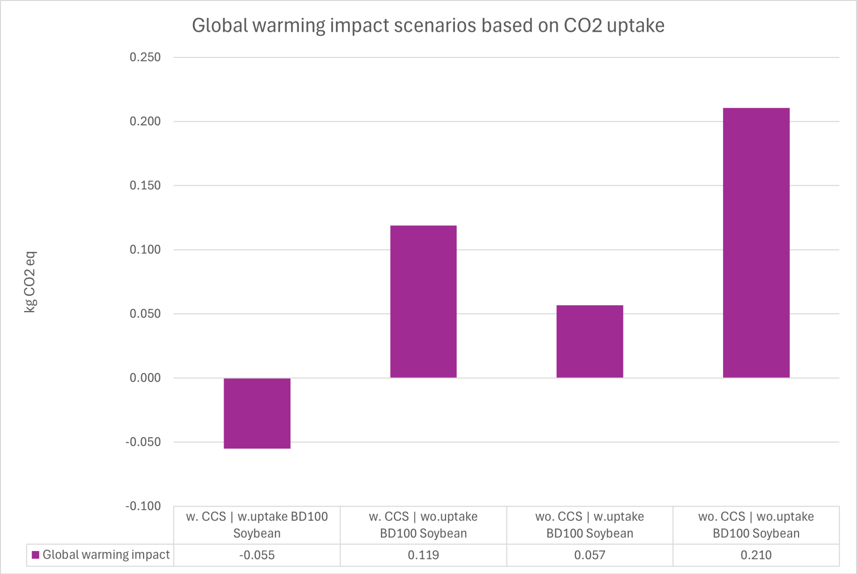


Figure 25: Global warming potential difference when considering CO_2 uptake in biomass for product system 2.c) BD100 Soybean. The results are shown with and without uptake of CO_2 from the CCS

5.3 Biodiesel, difference depending on land usage change

The difference in GWP for different amounts of land use change was computed as an example in the case of BD100 RME. The results are shown in Figure 26.

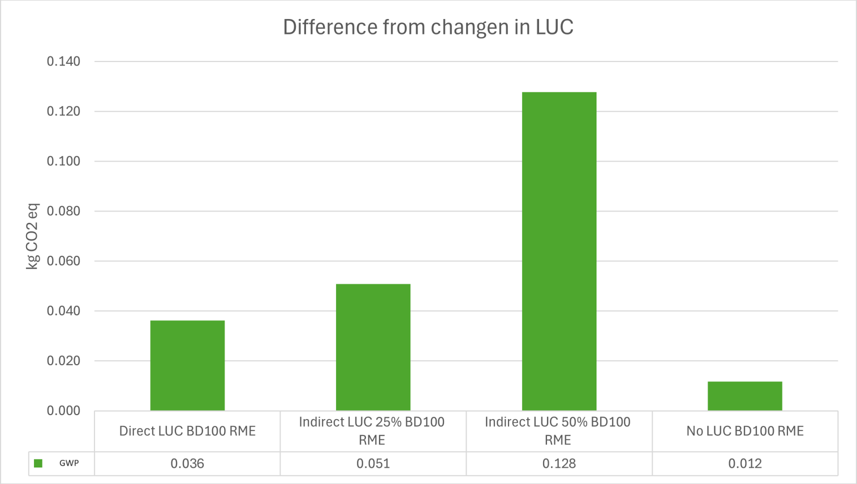
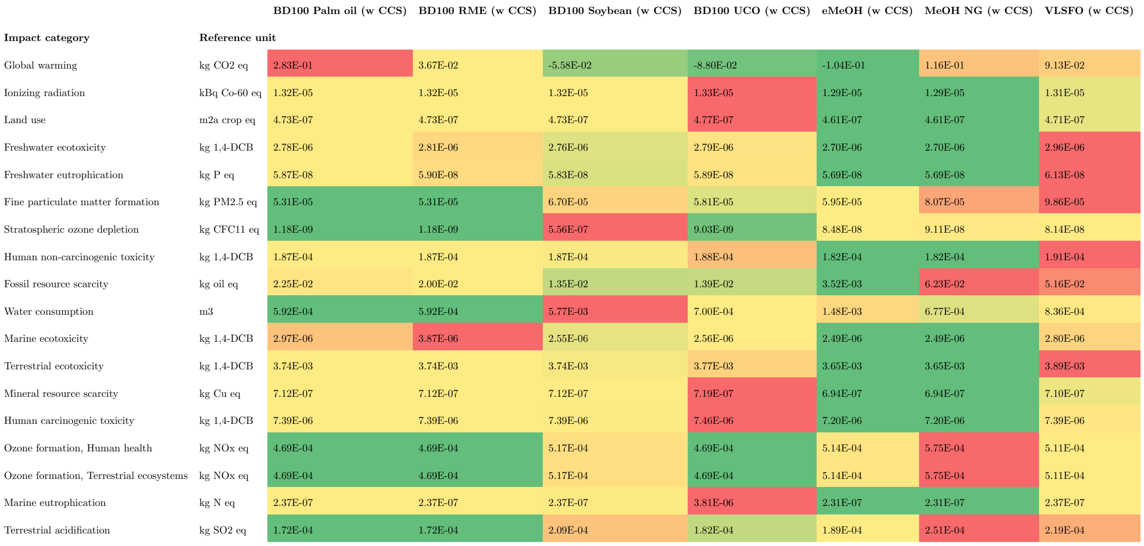


Figure 26: Effect from land use change on Product system 2.b) BD100 RME

5.4 Other Impact Categories

All impact categories accounted for in ReCiPe are shown in Figure 27 - 30. The provided picture illustrates the comparative indicator outcome of each system variation with the impact of CCS. Each indicator's maximum result is standardized to 100% and the results of the alternative variations are displayed relative to this benchmark. As seen in the figure not all impact categories have a value for all systems, because of missing data points. The missing data is due to limitations in GREET and flows included in the modeling of the CCS come from other databases that map to other impact categories as well.

Table 8: LCIA results for each product system with CCS. Green represents lower values and read represents higher values.



		BD100 Palm oil (w CCS)	BD100 RME (w CCS)	BD100 Soybean (w CCS)	BD100 UCO (w CCS)	eMeOH (w CCS)	MeOH NG (w CCS)	VLSFO (w CCS)
Impact category	**Reference unit**							
Global warming	kg CO2 eq	2.83E-01	3.67E-02	-5.58E-02	-8.80E-02	-1.04E-01	1.16E-01	9.13E-02
Ionizing radiation	kBq Co-60 eq	1.32E-05	1.32E-05	1.32E-05	1.33E-05	1.29E-05	1.29E-05	1.31E-05
Land use	m2a crop eq	4.73E-07	4.73E-07	4.73E-07	4.77E-07	4.61E-07	4.61E-07	4.71E-07
Freshwater ecotoxicity	kg 1,4-DCB	2.78E-06	2.81E-06	2.76E-06	2.79E-06	2.70E-06	2.70E-06	2.96E-06
Freshwater eutrophication	kg P eq	5.87E-08	5.90E-08	5.83E-08	5.89E-08	5.69E-08	5.69E-08	6.13E-08
Fine particulate matter formation	kg PM2.5 eq	5.31E-05	5.31E-05	6.70E-05	5.81E-05	5.95E-05	8.07E-05	9.86E-05
Stratospheric ozone depletion	kg CFC11 eq	1.18E-09	1.18E-09	5.56E-07	9.03E-09	8.48E-08	9.11E-08	8.14E-08
Human non-carcinogenic toxicity	kg 1,4-DCB	1.87E-04	1.87E-04	1.87E-04	1.88E-04	1.82E-04	1.82E-04	1.91E-04
Fossil resource scarcity	kg oil eq	2.25E-02	2.00E-02	1.35E-02	1.39E-02	3.52E-03	6.23E-02	5.16E-02
Water consumption	m3	5.92E-04	5.92E-04	5.77E-03	7.00E-04	1.48E-03	6.77E-04	8.36E-04
Marine ecotoxicity	kg 1,4-DCB	2.97E-06	3.87E-06	2.55E-06	2.56E-06	2.49E-06	2.49E-06	2.80E-06
Terrestrial ecotoxicity	kg 1,4-DCB	3.74E-03	3.74E-03	3.74E-03	3.77E-03	3.65E-03	3.65E-03	3.89E-03
Mineral resource scarcity	kg Cu eq	7.12E-07	7.12E-07	7.12E-07	7.19E-07	6.94E-07	6.94E-07	7.10E-07
Human carcinogenic toxicity	kg 1,4-DCB	7.39E-06	7.39E-06	7.39E-06	7.46E-06	7.20E-06	7.20E-06	7.39E-06
Ozone formation, Human health	kg NOx eq	4.69E-04	4.69E-04	5.17E-04	4.69E-04	5.14E-04	5.75E-04	5.11E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	4.69E-04	4.69E-04	5.17E-04	4.69E-04	5.14E-04	5.75E-04	5.11E-04
Marine eutrophication	kg N eq	2.37E-07	2.37E-07	2.37E-07	3.81E-06	2.31E-07	2.31E-07	2.37E-07
Terrestrial acidification	kg SO2 eq	1.72E-04	1.72E-04	2.09E-04	1.82E-04	1.89E-04	2.51E-04	2.19E-04

Table 9: LCIA results for each product system without CCS. Green represents lower values, red represents higher values and white represents missing or zero values

		BD100 Palm oil (wo CCS)	BD100 RME (wo CCS)	BD100 Soybean (wo CCS)	BD100 UCO (wo CCS)	eMeOH (wo CCS)	MeOH NG (wo CCS)	VLSFO (wo CCS)
Impact category	**Reference unit**							
Global warming	kg CO2 eq	3.52E-01	1.37E-01	5.66E-02	2.94E-02	1.14E-02	1.92E-01	1.86E-01
Ionizing radiation	kBq Co-60 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Land use	m2a crop eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Freshwater ecotoxicity	kg 1,4-DCB	8.70E-09	3.19E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.77E-07
Freshwater eutrophication	kg P eq	3.05E-10	5.92E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.83E-09
Fine particulate matter formation	kg PM2.5 eq	4.60E-05	4.60E-05	5.81E-05	5.04E-05	4.86E-05	6.60E-05	8.65E-05
Stratospheric ozone depletion	kg CFC11 eq	9.84E-10	9.84E-10	4.85E-07	7.83E-09	6.97E-08	7.48E-08	7.17E-08
Human non-carcinogenic toxicity	kg 1,4-DCB	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.29E-06
Fossil resource scarcity	kg oil eq	1.95E-02	1.73E-02	1.17E-02	1.20E-02	2.79E-03	5.11E-02	4.54E-02
Water consumption	m3	1.72E-17	1.72E-17	4.51E-03	8.91E-05	7.45E-04	8.26E-05	2.17E-04
Marine ecotoxicity	kg 1,4-DCB	3.62E-07	1.14E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.22E-07
Terrestrial ecotoxicity	kg 1,4-DCB	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.44E-04
Mineral resource scarcity	kg Cu eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.32E-10
Human carcinogenic toxicity	kg 1,4-DCB	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.71E-08
Ozone formation, Human health	kg NOx eq	4.09E-04	4.09E-04	4.51E-04	4.09E-04	4.22E-04	4.73E-04	4.50E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	4.09E-04	4.09E-04	4.51E-04	4.09E-04	4.22E-04	4.73E-04	4.50E-04
Marine eutrophication	kg N eq	0.00E+00	0.00E+00	0.00E+00	3.12E-06	0.00E+00	0.00E+00	8.95E-10
Terrestrial acidification	kg SO2 eq	1.49E-04	1.49E-04	1.81E-04	1.58E-04	1.55E-04	2.06E-04	1.92E-04

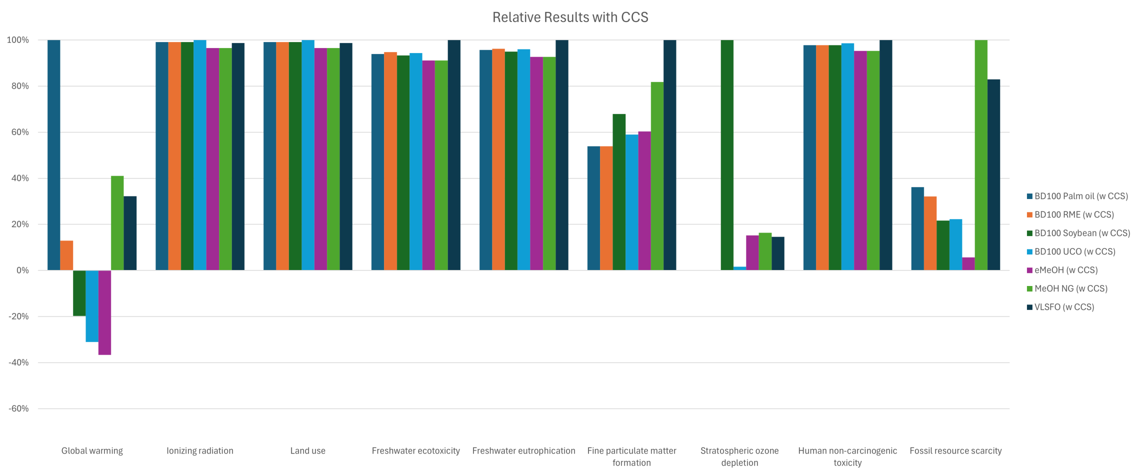


Figure 27: Relative Results from the LCIA with CCS

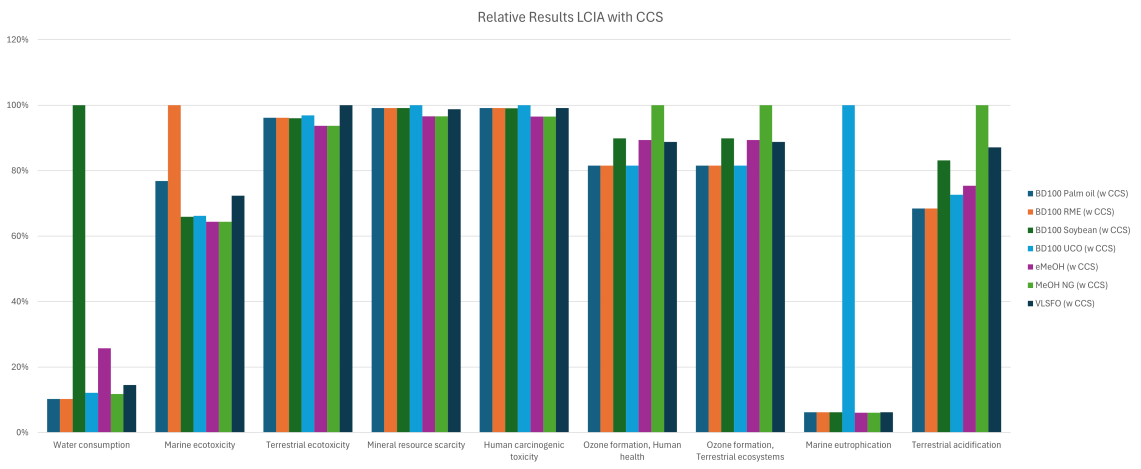


Figure 28: Relative Results from the LCIA with CCS

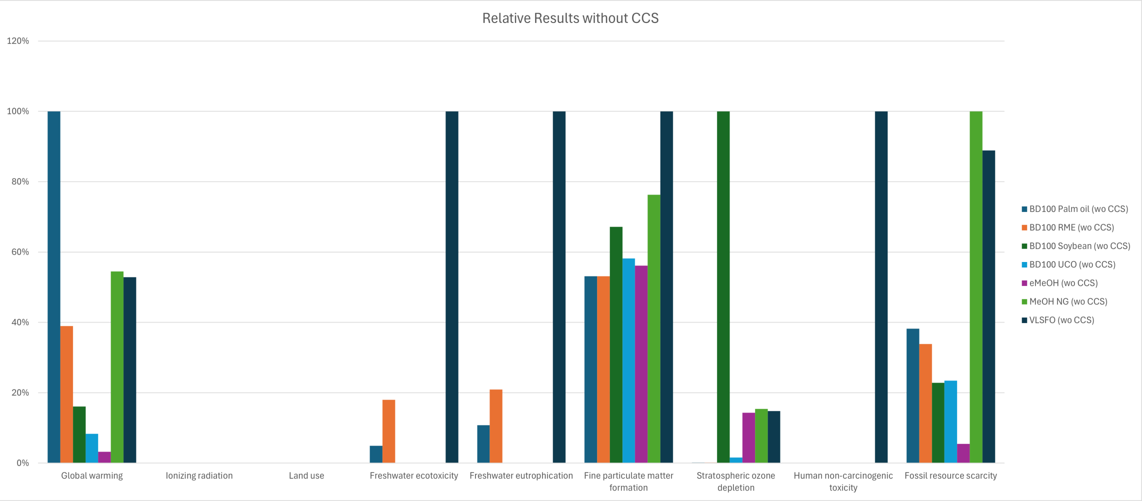


Figure 29: Relative Results from the LCIA without CCS

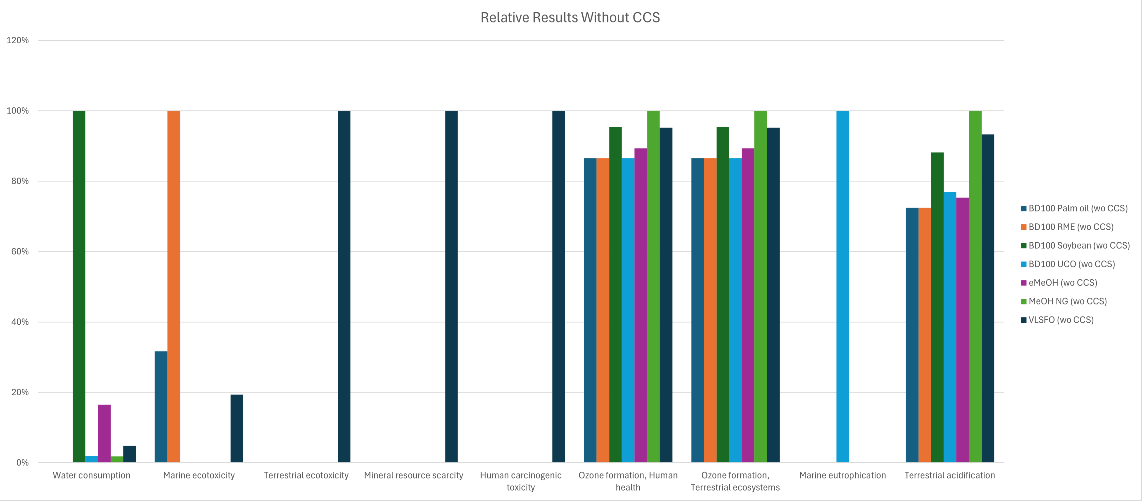
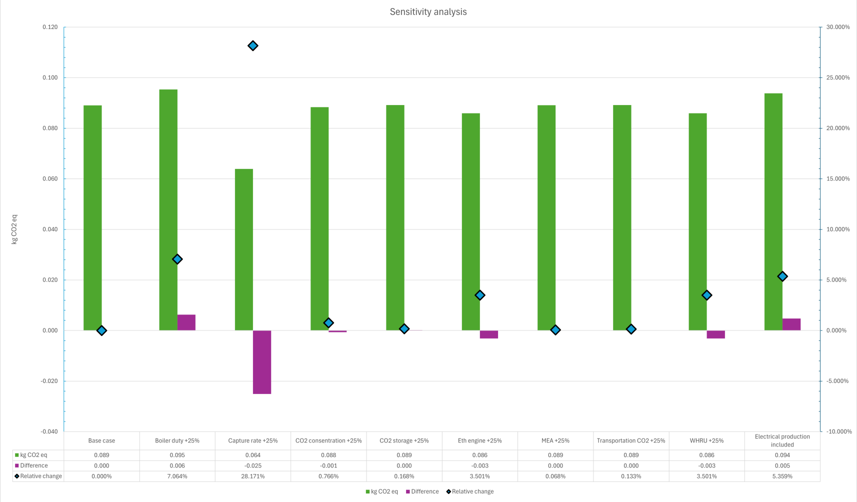


Figure 30: Relative Results from the LCIA without CCS

5.5 Sensitivity analysis

A one-at-a-time perturbation approach was used to assess the individual impact of the moving parameters included in the study. The moving parameters have been defined as the parameters calculated and interpreted from other works of literature and does not include upstream processes taken directly from databases such as GREET, ProBas, and Ecoinvent. Different allocation methods for the project have not been included in the sensitivity analysis as the system only has one usable output; power on the shaft. The total $kgCO_2eq$, difference from the baseline and the relative absolute effects can be seen in Figure 31.



	Base case	Boiler duty +25%	Capture rate +25%	CO2 consentration +25%	CO2 storage +25%	Eth engine +25%	MEA +25%	Transportation CO2 +25%	WHRU +25%	Electrical production included
■ kg CO2 eq	0.089	0.095	0.064	0.088	0.089	0.086	0.089	0.089	0.086	0.094
■ Difference	0.000	0.006	-0.025	-0.001	0.000	-0.003	0.000	0.000	-0.003	0.005
◆ Relative change	0.000%	7.064%	28.171%	0.766%	0.168%	3.501%	0.068%	0.133%	3.501%	5.359%

Figure 31: OAT sensitivity analysis of foreground variables

5.6 Monte Carlo

The Monte Carlo simulation allows the parameters to be simulated using a normal distribution with a standard deviation of 10% per variable to assess the spread of the data using random samples for a simulation length of 10000 iterations. The parameters were the following: the thermal energy needed to power the CCS, the emissions from the engine, the MEA consumption of the CCS, the transportation distance of the liquefied CO_2, the efficiency of the engine, and the carbon emission related to permanently storing CO_2. (The Monte Carlo simulation can include unrealistic values, impossible for an actual system.)

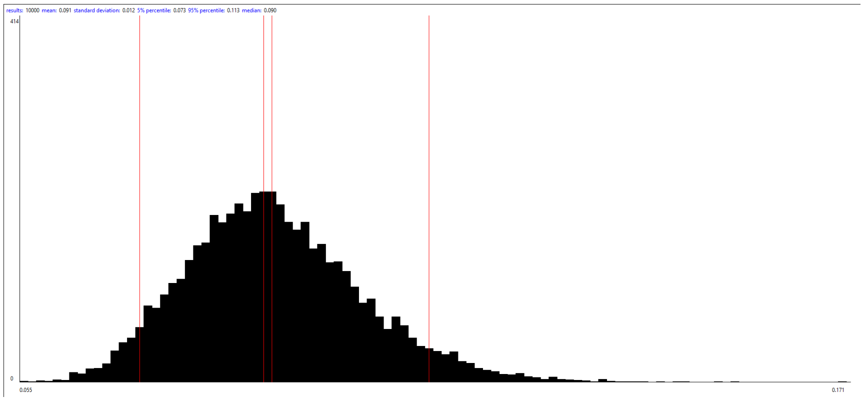
$$\sigma = 0.012 \tag{21}$$

$$N = 10000 \tag{22}$$

$$Mean = 0.091 \tag{23}$$

$$\alpha = 5\% \tag{24}$$

$$Confidence.interval_{95\%} = 0.091 \pm 0.00024 \tag{25}$$



results: 10000 mean: 0.091 standard deviation: 0.012 5% percentile: 0.073 95% percentile: 0.113 median: 0.090

Figure 32: Monte Carlo (VLSFO) from OpenLCA

6 Discussion

In this chapter, the results from the previous chapter will be discussed.

6.1 Impact of Database

When discussing the results, it is important to mention the differences in the use of databases. As shown in Figure 24 it seems like palm oil affects global warming almost twice as much as VLSFO. It is important to remember that data points for BD100 Palm oil and BD100 RME production pathways are taken from ProBas, while all other fuel pathways are taken from GREET. This means that different assumptions might have been made e.g. different allocation methods. Therefore, a comparison between the different datasets should be done with great caution, since the relative results between the datasets might differ. However, if comparing the results in this study made by Chen et al. and Siregar et al. the results seem reasonable. [76] [35] Comparison between the fuels using the same database can however be done.

6.2 Global Warming Impact Without CCS

When observing the GWP results from GREET in Figure 24 it can be stated that green methanol has the least impact on global warming, while methanol produced from natural gas has the second greatest impact. This implies that contribution from the fuel upstream processes influences the results markedly. According to the methanol institute [77] the life cycle carbon footprint can be reduced by more than 90% if using e-methanol instead of natural gas-based methanol. This is in line with the results of this study with a GWP reduction of around 95%. Moreover, according to Su et. al [39] the total CO_2 emissions can be reduced by around 70% by using green methanol instead of conventional. The difference in results might depend on differences in the scope. Su. et al only mention CO_2 emissions, while this study includes other emissions that also affect global warming, which could give a higher value for the natural gas in this study.

Furthermore, it is noticed that methanol from natural gas gives an even greater GWP than VLSFO, which not only depends on emissions during methanol synthesis but also because of the lower heating value of methanol, meaning a much higher fuel consumption for the same amount of energy on the shaft.

Moreover, comparing the different biodiesel, it is stated that biodiesel from palm oil has the most impact on global warming. This great impact could depend on the high environmental cost of the production and the long fuel transportation. This fuel pathway, taken from ProBas, accounts for palm oil from Indonesia, which entails longer transportation of the fuel compared to the ones produced in EU and the US. Also, biodiesel made from palm oil has a high environmental impact during the production pathway. According to Siregar et. al [35] the high GWP could be explained by the great emissions of methane from palm oil mill effluent and fertilizing process during the cultivation of palm oil and the land use change from growing the palm-biomass. The lowest emissions come from the BD100 UCO, a biofuel made from waste products that do not contribute to additional land mass being occupied by the growing of foods.

6.3 Global Warming Impact With CCS

Observing the results with the influence of CCS compared to the results without (see Figure 24), it can be stated that the CCS has a great impact on the results. It is noticed that the GWP for all product systems has decreased, and several systems have a negative impact. The cases using fossil fuels will always have a positive value since all emissions released into the air will increase the GWP and nothing during fuel production contributes to CO_2 sequestration. If it was possible to capture all emissions from the product system it could as best receive a neutral GWP if the entire upstream was CO_2 neutral. The non-fossil fuels have the potential to reach net negative CO_2 emissions as some form of carbon sequestration occurs during fuel production. Biofuels remove CO_2 from the atmosphere and store it in the biomass and green methanol stores CO_2 from industrial processes.

A correlation can be seen from the results in Chapter 5.1 that the greatest total reduction in GWP is achieved by the fuels with the lowest upstream production impact. This is because the OCCS contributes to additional fuel consumption.

There is reason to be cautious about the extent of the impact of green methanol. The upstream processes from green methanol are taken from the GREET database and how GREET allocates CO_2 from a well-to-pump perspective has been mentioned in Chapter 2.4. The case with the green methanol included in this thesis has 61.88% of the captured CO_2 come from natural gas processes (see Appendix). The burden of the upstream emission seems to be allocated mainly to the point source emitters in the upstream and little burden is allocated to the fuel itself. The more critical way to calculate the emission would be to imagine all fossil emissions as zero until they are released into the atmosphere. For example, a coal power plant digs up 1 mol of coal and burns it in their power plant. The 1 mol of carbon becomes 1 mol of CO_2 that is captured and stored. It is then used to make fuel. It is currently at net zero carbon emissions as the CO_2 is still stored in the fuel, storing it forever would keep it at net zero. Instead, it is combusted and the 1 mol of CO_2 is released and not captured again, making the total emissions from the entire cradle-to-grave emissions carbon positive. This burden should then be shared among the CO_2 emitters proportionally. The argument against this shared burden is that it can allow the big point source emitters to claim that their activity is more sustainable than it is and expansion of relatively high-emitting industries can occur instead of the transition toward greener alternatives.

The biofuel is more straightforward. Some of the fuels have low enough upstream emissions that the CO_2 uptake from the biomass and the permanent CO_2 storage is enough to compensate. This is not the case for BD100RME or BD100 Palm oil. The BD100 RME is close to reaching net zero and an increase in the capture rate would allow for the global warming impact to be reduced.

Since this study does not include the manufacturing phase of the CCS, environmental impacts linked to it are missing e.g emissions, used materials, and energy usage during the manufacturing. The omission of some life-cycle processes could potentially present the CCS in a more favorable way than reality and should therefore be taken into consideration. Manufacturing should be further investigated to get the whole cradle-to-grave perspective of the CCS.

6.4 Difference in Accounting Methods for Biofuels

The method of allocating emissions for biodiesel is a complex topic discussed earlier in Chapter 3.1.2 and to display the large difference from different accounting methods Figure 25 and 26 was constructed from the LCI results and calculated into an LCIA result of GWP.

CO_2 Uptake The CO_2 stored in the biomass accounts for a net negative CO_2 balance to the atmosphere after production for the BD100 Soybean, the net negative is subsequently increased by the same amount of CO_2 released to the atmosphere after combustion. This way of accounting is recognized by several organizations [78] [79] and follows the assumption of CO_2 balance. It can be shown from the results that biofuel has the potential to remove CO_2 permanently from the atmosphere but that is only the case if the CO_2 uptake is large enough compared to the emissions from production, transport, etc.

Land Usage Change The impact of different land use changes has been discussed earlier and the difference for the BD100 RME is shown in Table 26 to further illustrate the drastic impact to global warming potential if the crops cause any type of land usage change. It is stated by Sammy El Takriti et.al. [32] that the demand for low land use impacting biofuels is rising as the need to reach greater climate regulations increases. The use of waste to produce biofuels has also been indicated by the results in Table 24 to be the biofuel with the lowest global warming impact.

This report mainly focuses on global warming impact. The aggregation of crops affects the local ecosystems among other things and other impact categories should be considered to come to a full conclusion regarding the benefits and threats of using biofuels.

6.5 Impact of Other Impact Categories

GREET focuses on GWP and therefore other impact categories are missing data points to make legitimate conclusions from the fuel streams alone. In the study made by Kanchirallan et.al [1] the decrease of GWP seems to entail some trade-offs, like human toxicity or freshwater ecotoxicity. From Figure 27 - 30 it is possible to identify that all impact categories are affected and it seems like most of the impact in the other categories comes after the CCS is added. There can not be any conclusion drawn from this except that the CCS will affect all impact categories in some way. However, it can not be determined if this impact would have been noticeable if the fuel upstream was modeled with the other categories in mind.

6.6 Quality of the Model

Two numerical methods were employed to verify the model parameters (see Chapter 5.5 and 5.6). The sensitivity analysis in Figure 31 indicates that no single parameter tested has a large impact on the total global warming output, instead other parameters like fuel production for the different fuel types and emissions during combustion are the main deciders of the total global warming for each product system. Two exceptions to this are the capture rate and the inclusion of electrical load. The capture rate, when increased by 25% gave a 28% response. An explanation for this is the relatively low impact from VLSFO production and a different result is expected when compared to fuels with the majority of the climate impact during production of the fuel.

The other example of a large impact was the inclusion of emissions related to the production of onboard electricity. This was done by moving energy output from the shaft to output for electricity production by the required amount to power the scrubber, SCR, and CCS. This is the equivalent of reducing the engine efficiency by the electrical load amount. The global warming impact was relatively large with an increase of approximately 5.4%. The scenario of reducing the output on the shaft is not the standard method of electricity generation and actual onboard electrical production commonly comes from other generators powered by other fuel than that of the engine (e.g diesel) [80]. This however indicates the importance of including the onboard power production in future more in-depth studies for an actual system implementation. It is however kept out from this report as the scope would grow to include more energy sources and it is assumed that the results would change almost equally relative to each case. Thus, the results when comparing the fuel systems to each other are still valid. A big difference could occur if the flue gasses are to pass through the exhaust gas treatment systems.

The Monte Carlo simulation from figure 32 was conducted to further investigate if some flows or variables were sensitive to change. The Monte Carlo simulation also supports the model not being reliant on a single or a few parameters for the total output.

The total energy consumption calculated in the model gives rise to 12.26% to 13.55% increase in total energy consumption according to Table 7. This value is within reason to other similar studies like Kanchiralla et.al [1] with an increase of 19%, Einbu et.al [16] with an increase of 6%-12% or Sridhar et.al [13] with a fuel penalty of 1.8% to 19%.

Parameters that have not been tested are flows from background processes like chemical production or fuel production. The amount of each resulting product flow (e.g monoethanolamine produced from the upstream process monoethanolamine production) is tested in the sensitivity analysis and the Monte Carlo simulation. It is assumed that the total impact of changing flow parameters in the background process would yield a small response to the total output as the response of changing the resulting flow was small. The difference in the production of fuels is assumed to be assessed by including several fuel types.

6.7 Sources of Errors

In the study, some parameters have not been taken into consideration which might have affected the result. Firstly, all physical parameters regarding the CCS have not been considered. For example, the modeled systems do not include sizing of the absorber and desorber. Previous studies discuss problems with space limitations onboard vessels and therefore sizing of the height and width of the column might be limited [12]. This could affect the performance of the CCS. Moreover, the change in transport work due to lost load has been neglected. Adding a CCS to a vessel will take up space that otherwise could have been used to transport goods. The additional transportation weight will lead to added emissions. Furthermore, the engine load has not been taken into account. During operation, the engine load will vary, for example during cruising and maneuvering of the vessel. Also, the engine load will increase due to the added weight from the CCS technology itself and the captured CO_2. This will affect both the fuel consumption and the emissions. However, in this study, the engine load is assumed to be unaffected which is a simplification compared to reality.

6.8 What is Slowing the Transition to Renewable Fuels

The need for low-emission solutions is urgent and implementing new technologies as soon as possible to reach the IMO goals is needed. The systems investigated in this report are a possibility for this as seen in the results and further discussed in section Chapter

6. However, several challenges are involved with converting the theoretical model to a real-world option.

Capacity limitations As mentioned in chapter 3.1.2, biofuels have several challenges. One is the limitation of the total capacity of producible biofuel [81]. IEA believes that the shortage of available feedstock can be mitigated by seeking out new supply chains. This could, however, lead to more food going to fuel production, another feedstock, or new farmland being produced that could lead to native biospheres being pushed aside for fuel production. There are however opportunities with biofuels and if the transition is done responsibly and each impact factor is carefully monitored during a large-scale implementation, biofuels could be a promising replacement to fossil fuels.

Green methanol is the clear winner when reviewing the total well-to-wake global warming impact found from the results. These results display the great potential of electro fuels if they are produced by green electricity and care is taken during combustion to limit the emissions to the atmosphere. But green methanol suffers even more than biofuels when reviewing the total capacity of production, making it a solution that is dependent on how the market for green methanol develops over time. A change that is projected to happen and the total capacity to go from almost none to 22.4 Mt/year in 2029 [77]. 22.4 Mt/year is approximately 3.4% of the total projected fuel consumption by the maritime industry in 2030 [82], and about 1.6% if the lower heating value is considered.

Cost This report does not have cost within its life cycle scope but it will be a relevant factor when considering what option will be the easiest to implement. Only looking at the cost/toe of fuel there is currently a large difference in price for the different fuels as can be seen in Figure 33. These differences will be reduced over time and CO_2 emission costs need to match the increased fuel cost to make the green transition lucrative for the ship owners.

The cost analysis indicates that e-Methanol has the most to gain from the future market prices and will be cheaper than FAME by 2050 (see Figure 33).

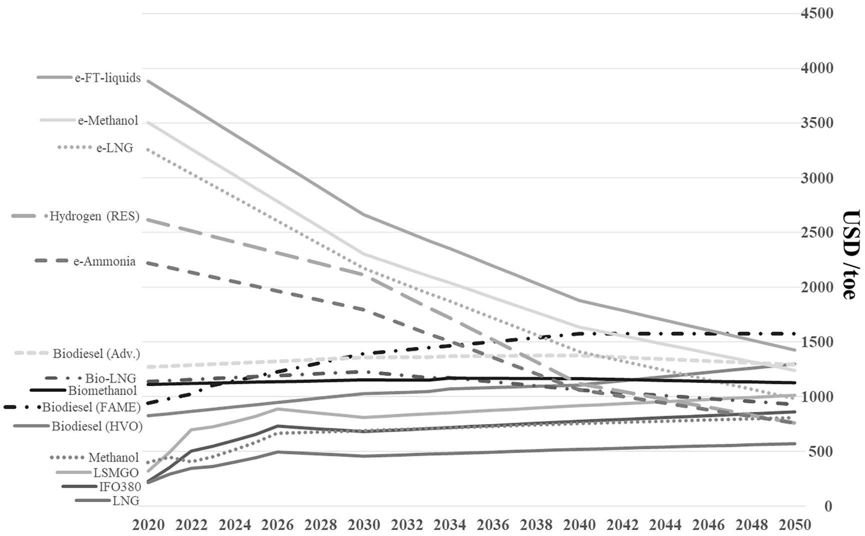


Figure 33: Projected fuel cost between 2020 and 2050 USD/toe [83]

7 Conclusion

The LCA carried out in this study can be used to answer the research questions initially posed.

Regarding which alternative fuel has the least impact on climate change, it can be concluded that both methanol and biofuels have great potential to reduce CO_2 emissions. However, it is important to consider how the fuel has been produced and make sure the entire process is clean. Otherwise, the impact of climate change might be worse than continuing with fossil fuels. With a completely green production like green methanol, the impact will be the lowest. Regarding biofuel using waste products like used cooking oil has the least effect on global warming.

Regarding CCS as a possible innovation to reduce CO_2eq emissions, it has great potential which is shown by the thesis result. The CO_2eq emissions will be reduced significantly regardless of which fuel is used, with fuels having a lower environmental impact during production, receiving a greater total GWP reduction from the OCCS. However, the CCS technology has other trade-offs that affect the environment differently, which must be considered.

With this in mind, it can finally be stated which product system has the best potential to fulfill the IMO 2050 goal. It is concluded that all the examined product systems displayed reduced global warming potential with the CCS. The reduction is despite increased fuel consumption and permanent storage included. The results indicate that using a CCS onboard the shipping vessel could be a possible solution to reduce the maritime industry's emissions. The combination of systems should then be green-methanol as far as possible and then use biodiesel from waste products like used cooking oil. Other feedstock is also relevant but care of which one and how that specific feedstock relates to the land use change is needed to effectively reduce the greenhouse gas emissions.

Other impacts from the CCS have not been able to be concluded due to a lack of data on the fuel production pathways.

7.1 Further Research

First of all this thesis focuses on decreasing GHG emissions to reduce the impact of climate change. However, there are other environmental concerns to take into account. Further research could be done by choosing a database that focuses on other impact categories as well. Furthermore, the manufacturing phase of the CCS was not included, which might have a great impact on the environment.

In addition, a more in-depth model of how the onboard CCS and the ship systems interact could receive better operation parameter values. For future research, this can be done using simulation software, leading to greater insight into how fuel parameters affect the OCCS performance.

A more in-depth analysis of how the fuel pathways affect the global warming reduction from the OCCS and a comparison among different databases should also be conducted to identify problems and opportunities by including an OCCS. Future studies should also compare the impact of utilizing the captured CO_2 instead of permanently storing it to investigate the impact from a more circular CO_2 life-cycle.

References

[1] F. M. Kanchiralla, S. Brynolf, E. Malmgren, J. Hansson, and M. Grahn, "Life-Cycle Assessment and Costing of Fuels and Propulsion Systems in Future Fossil-Free Shipping," *Environmental Science & Technology*, vol. 56, no. 17, pp. 12 517–12 531, Sep. 2022. [Online]. Available: https://pubs.acs.org/doi/10.1021/acs.est.2c03016

[2] I. M. Organization, "Fourth Greenhouse Gas Study 2020," 2020. [Online]. Available: https://www.imo.org/en/ourwork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

[3] T. t. p. g. i. S. a. n. l. f. t. i. g. b. c. o. c. D. t. v. u. cycles and S. C. D. M. u.-t.-D. D. T. R. i. t. Text, "Topic: Ocean shipping." [Online]. Available: https://www.statista.com/topics/1728/ocean-shipping/

[4] UNCTAD, "Review of Maritime Transport 2022 | UNCTAD." [Online]. Available: https://unctad.org/rmt2022

[5] T. Boningari and P. G. Smirniotis, "Impact of nitrogen oxides on the environment and human health: Mn-based materials for the NOx abatement," *Current Opinion in Chemical Engineering*, vol. 13, pp. 133–141, Aug. 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2211339816300661

[6] I.-M. Gren, A. Brutemark, and A. Jägerbrand, "Air pollutants from shipping: Costs of NOx emissions to the Baltic Sea," *Journal of Environmental Management*, vol. 300, p. 113824, Dec. 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301479721018867

[7] A. Mukherjee and M. Agrawal, "A Global Perspective of Fine Particulate Matter Pollution and Its Health Effects," in *Reviews of Environmental Contamination and Toxicology Volume 244*, P. de Voogt, Ed. Cham: Springer International Publishing, 2018, pp. 5–51. [Online]. Available: https://doi.org/10.1007/398_2017_3

[8] E. E. Agancy, "Facts and figures: the EMTER report," 2021.

[9] MARINE ENVIRONMENT PROTECTION COMMITTEE, "2023 IMO STRATEGY ON REDUCTION OF GHG EMISSIONS FROM SHIPS," Jul. 2023. [Online]. Available: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/annex/MEPC%2080/Annex%2015.pdf

[10] M. Latarche, "Exhaust emissions and control," in *Pounder's Marine Diesel Engines and Gas Turbines.* Elsevier, 2021, pp. 87–115. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/B9780081027486000049

[11] S. Brynolf, “Environmental Assessment of Present and Future Marine Fuels,” Ph.D. dissertation, Chalmers University of Technology, Gothenburg, 2014.

[12] J. Oh, D. Kim, S. Roussanaly, R. Anantharaman, and Y. Lim, “Optimal capacity design of amine-based onboard CO2 capture systems under variable marine engine loads,” *Chemical Engineering Journal*, vol. 483, p. 149136, Mar. 2024. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1385894724006211

[13] P. Sridhar, A. Kumar, S. Manivannan, S. Farooq, and I. A. Karimi, “Technoeconomic evaluation of post-combustion carbon capture technologies on-board a medium range tanker,” *Computers & Chemical Engineering*, vol. 181, p. 108545, Feb. 2024. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0098135423004155

[14] “Concept of LCA.” [Online]. Available: https://www.wind-energy-the-facts.org/concept-of-lca.html

[15] H. Suleman, P. L. Fosbøl, R. Nasir, and M. Ameen, Eds., *Sustainable Carbon Capture: Technologies and Applications.* Boca Raton: CRC Press, Feb. 2022.

[16] A. Einbu, T. Pettersen, J. Morud, A. Tobiesen, C. Jayarathna, R. Skagestad, and G. Nysæther, “Energy assessments of onboard CO2 capture from ship engines by MEA-based post combustion capture system with flue gas heat integration,” *International Journal of Greenhouse Gas Control*, vol. 113, p. 103526, Jan. 2022. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1750583621002772

[17] “Environmental management - Life cycle assessmen - Principles and framework,” 2006.

[18] “Environmental management - Life cycle assessment - Requirments and guidelines (ISO 14044:2006),” 2006.

[19] O. US EPA, “Understanding Global Warming Potentials,” Jan. 2016. [Online]. Available: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

[20] M. Huijbregts, “ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level,” 2016. [Online]. Available: https://drive.google.com/drive/u/0/folders/1yb7K_pMnkU7akVZ-b0jWVz2jfeE4J1L8

[21] I. P. on Climate Change, “2.10.2 Direct Global Warming Potentials - AR4 WGI Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing.” [Online]. Available: https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html

[22] N. Von Der Assen, J. Jung, and A. Bardow, “Life-cycle assessment of carbon dioxide capture and utilization: avoiding the pitfalls,” *Energy & Environmental Science*, vol. 6, no. 9, p. 2721, 2013. [Online]. Available: http://xlink.rsc.org/?DOI=c3ee41151f

[23] VPS, “2023 MARINE BUNKER FUELS REVIEW | VPS.” [Online]. Available: https://www.vpsveritas.com/knowledgecentre/articles/2023-marine-bunker-fuels-review

[24] A. E. Zvereva, M. A. Ershov, V. D. Savelenko, M. M. Lobashova, M. Y. Rogova, U. A. Makhova, E. O. Tikhomirova, N. O. Burov, D. R. Aleksanyan, V. M. Kapustin, E. A. Chernysheva, and A. I. Rakova, “Use of Asphaltene Stabilizers for the Production of Very Low Sulphur Fuel Oil,” *Energies*, vol. 16, no. 22, p. 7649, Nov. 2023. [Online]. Available: https://www.mdpi.com/1996-1073/16/22/7649

[25] “Biofuel | Definition, Renewable Energy, Types, & Pros and Cons | Britannica.” [Online]. Available: https://www.britannica.com/technology/biofuel

[26] “Generations of biofuels | Introduction to Biofuel: Perennial Grasses as a Feedstock - passel.” [Online]. Available: https://passel2.unl.edu/view/lesson/b983ed434704/4

[27] E. C. D. Tan, K. Harris, S. M. Tifft, D. Steward, C. Kinchin, and T. N. Thompson, “Adoption of biofuels for marine shipping decarbonization: A long-term price and scalability assessment,” *Biofuels, Bioproducts and Biorefining*, vol. 16, no. 4, pp. 942–961, Jul. 2022. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1002/bbb.2350

[28] E. C. D. Tan, T. R. Hawkins, U. Lee, L. Tao, P. A. Meyer, M. Wang, and T. Thompson, “Biofuel Options for Marine Applications: Technoeconomic and Life-Cycle Analyses,” *Environmental Science & Technology*, vol. 55, no. 11, pp. 7561–7570, Jun. 2021. [Online]. Available: https://pubs.acs.org/doi/10.1021/acs.est.0c06141

[29] “Alternative Fuels Data Center: Biodiesel Production and Distribution.” [Online]. Available: https://afdc.energy.gov/fuels/biodiesel_production.html

[30] T. D. Searchinger, T. Beringer, and A. Strong, “Does the world have low-carbon bioenergy potential from the dedicated use of land?” *Energy Policy*, vol. 110, pp. 434–446, Nov. 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301421517305104

[31] Z. M. Harris, S. Milner, and G. Taylor, “Biogenic Carbon—Capture and Sequestration,” in *Greenhouse Gases Balances of Bioenergy Systems*. Elsevier, 2018, pp. 55–76. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/B9780081010365000057

[32] Sammy El Takriti, Stephanie Searle, and Chris Malins, "Understanding options for ILUC mitigation," Nov. 2016. [Online]. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://theicct.org/sites/default/files/publications/ILUC-Mitigation-Options_ICCT_nov2016.pdf

[33] "Land Use, Land-Use Change and Forestry (LULUCF) | UNFCCC." [Online]. Available: https://unfccc.int/topics/land-use/workstreams/land-use--land-use-change-and-forestry-lulucf

[34] K. Winkler, R. Fuchs, M. Rounsevell, and M. Herold, "Global land use changes are four times greater than previously estimated," *Nature Communications*, vol. 12, no. 1, p. 2501, May 2021. [Online]. Available: https://www.nature.com/articles/s41467-021-22702-2

[35] K. Siregar, H. Sofyan, I. S. Nasution, R. Ichwana, S. Syafriandi, Sholihati, I. Sofiah, and T. Miharza, "Study of life cycle assessment in biodiesel production from crude palm oil and its benefits for the sustainability of oil palm industry in Aceh province Indonesia," *IOP Conference Series: Earth and Environmental Science*, vol. 644, no. 1, p. 012017, Jan. 2021. [Online]. Available: https://iopscience.iop.org/article/10.1088/1755-1315/644/1/012017

[36] Z. Tian, Y. Wang, X. Zhen, and Z. Liu, "The effect of methanol production and application in internal combustion engines on emissions in the context of carbon neutrality: A review," *Fuel*, vol. 320, p. 123902, Jul. 2022. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S001623612200761X

[37] N. E. T. Laboratory, "10.3. Syngas Conversion to Methanol." [Online]. Available: https://netl.doe.gov/research/carbon-management/energy-systems/gasification/gasifipedia/methanol

[38] S.-J. Jo, T.-H. Kang, B.-J. Shin, J.-H. Mun, S. Devkota, J.-Y. Cha, S. A. Mazari, K.-M. Kim, U. Lee, C.-H. Shin, and J.-H. Moon, "Internal carbon loop strategy for methanol production from natural gas: Multi-objective optimization and process evaluation," *Journal of Cleaner Production*, vol. 418, p. 138140, Sep. 2023. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0959652623022989

[39] C. Su, H. Wei, Z. Wang, H. Ayed, A. Mouldi, and A. A. Shayesteh, "Economic accounting and high-tech strategy for sustainable production: A case study of methanol production from CO2 hydrogenation," *International Journal of Hydrogen Energy*, vol. 47, no. 62, pp. 25 929–25 944, Jul. 2022. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0360319922002415

[40] S. MAN, 2024.

[41] L. Tan, Y. Guo, Z. Liu, P. Feng, and Z. Li, “An investigation on the catalytic characteristic of NO reduction in SCR systems,” *Journal of the Taiwan Institute of Chemical Engineers*, vol. 99, pp. 53–59, Jun. 2019. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1876107019300847

[42] Y. Zhang, D. Lou, P. Tan, Z. Hu, and L. Fang, “Effect of SCR downsizing and ammonia slip catalyst coating on the emissions from a heavy-duty diesel engine,” *Energy Reports*, vol. 8, pp. 749–757, Nov. 2022. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2352484721014475

[43] J. Yang, T. Tang, Y. Jiang, G. Karavalakis, T. D. Durbin, J. Wayne Miller, D. R. Cocker, and K. C. Johnson, “Controlling emissions from an ocean-going container vessel with a wet scrubber system,” *Fuel*, vol. 304, p. 121323, Nov. 2021. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0016236121012023

[44] S. Sethi, “A Guide To Scrubber System On Ship,” Mar. 2021. [Online]. Available: https://www.marineinsight.com/tech/scrubber-system-on-ship/

[45] H. Yamada, “Amine-based capture of CO2 for utilization and storage,” *Polymer Journal*, vol. 53, no. 1, pp. 93–102, Jan. 2021. [Online]. Available: https://www.nature.com/articles/s41428-020-00400-y

[46] B. J. Drewry and G. T. Rochelle, “Simple model for water wash performance in amine scrubbing for CO2 capture,” *Carbon Capture Science & Technology*, vol. 11, p. 100186, Jun. 2024. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2772656823000908

[47] L. Jiang, Z. Chen, S. Farouq Ali, J. Zhang, Y. Chen, and S. Chen, “Storing carbon dioxide in deep unmineable coal seams for centuries following underground coal gasification,” *Journal of Cleaner Production*, vol. 378, p. 134565, Dec. 2022. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0959652622041373

[48] H. Mikulčić, I. Ridjan Skov, D. F. Dominković, S. R. Wan Alwi, Z. A. Manan, R. Tan, N. Duić, S. N. Hidayah Mohamad, and X. Wang, “Flexible Carbon Capture and Utilization technologies in future energy systems and the utilization pathways of captured CO2,” *Renewable and Sustainable Energy Reviews*, vol. 114, p. 109338, Oct. 2019. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1364032119305465

[49] M. Bentham and M. Kirby, “CO $_2$ Storage in Saline Aquifers,” *Oil & Gas Science and Technology*, vol. 60, no. 3, pp. 559–567, May 2005. [Online]. Available: http://ogst.ifpenergiesnouvelles.fr/10.2516/ogst:2005038

[50] "Club CO2 - Deep saline Aquifers." [Online]. Available: https://www.club-co2.fr/en/content/deep-saline-aquifers

[51] "Northern Lights, the First Major Carbon Capture and Storage Project in Norway," May 2024. [Online]. Available: https://totalenergies.com/projects/carbon-capture-and-storage/northern-lights-first-major-carbon-capture-and-storage-project

[52] M. Feenstra, J. Monteiro, J. T. van den Akker, M. R. M. Abu-Zahra, E. Gilling, and E. Goetheer, "Ship-based carbon capture onboard of diesel or LNG-fuelled ships," *International Journal of Greenhouse Gas Control*, vol. 85, pp. 1–10, Jun. 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1750583618307758

[53] W. Chung and J. H. Lee, "Input–Output Surrogate Models for Efficient Economic Evaluation of Amine Scrubbing CO $_2$ Capture Processes," *Industrial & Engineering Chemistry Research*, vol. 59, no. 42, pp. 18 951–18 964, Oct. 2020. [Online]. Available: https://pubs.acs.org/doi/10.1021/acs.iecr.0c02971

[54] "Environment: treading lightly on the Earth." [Online]. Available: https://www.open.edu/openlearn/nature-environment/environmental-studies/environment-treading-lightly-on-the-earth/content-section-1.3.1

[55] IMO, "Fuel mass to CO2 mass conversion by carbon content of fuel." [Online]. Available: https://www.imorules.com/GUID-E5C63111-0AB7-4F8D-97B5-C7A4EC7748C4.html

[56] J. Licki, A. Pawelec, Z. Zimek, and S. Witman-Zajac, "Electron beam treatment of simulated marine diesel exhaust gases," *Nukleonika*, vol. 60, Sep. 2015.

[57] D. Aparecido Lopes Silva, A. Oliveira Nunes, V. Aparecida da Silva Moris, C. Moro Piekarski, and T. Oliveira Rodrigues, "(PDF) How important is the LCA software tool you choose Comparative results from GaBi, openLCA, SimaPro and Umberto," 2017. [Online]. Available: https://www.researchgate.net/publication/318217178_How_important_is_the_LCA_software_tool_you_choose_Comparative_results_from_GaBi_openLCA_SimaPro_and_Umberto

[58] S. Parts, "Market analysis of marine low speed diesel engine brand," May 2019. [Online]. Available: https://shipparts.wordpress.com/2019/05/27/market-analysis-of-marine-low-speed-diesel-engine-brand/

[59] "10 Largest Ports in North America." [Online]. Available: https://www.shipafreight.com/knowledge-series/largest-ports-in-north-america/

[60] “Port of Rotterdam,” Apr. 2024, page Version ID: 1217707025. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Port_of_Rotterdam&oldid=1217707025

[61] A. N. Laboratory, “Summary of Expansions and Updates in GREET® 2021,” 2021.

[62] “Heat exchangers (2022).” [Online]. Available: https://www.ipieca.org/resources/energy-efficiency-database/heat-exchangers-2022

[63] Z. Liang, X. Ma, H. Lin, and Y. Tang, “The energy consumption and environmental impacts of SCR technology in China,” *Applied Energy*, vol. 88, no. 4, pp. 1120–1129, Apr. 2011. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261910004058

[64] warstila, “SOx Scrubber systems.” [Online]. Available: https://www.wartsila.com/encyclopedia/term/sox-scrubber-systems

[65] J. Jee, “Hybrid Multi-Criteria Decision-Making for Marine SOx Scrubber Systems,” *Journal of Marine Science and Engineering*, vol. 10, p. 1599, Oct. 2022.

[66] R. v. Gijlswijk, PHM. Feron, and H. Oonk, “Environmental Impact of Solvent Scrubbing of CO2,” IEA Greenhous Gas R&D Programme, Netherlands, Tech. Rep. 2006/14, 2006. [Online]. Available: https://ieaghg.org/docs/General_Docs/Reports/2006-14%20Environmental%20Impact%20of%20Solvent%20Scrubbing%20of%20CO2.pdf

[67] A. Alabdulkarem, Y. Hwang, and R. Radermacher, “Development of CO2 liquefaction cycles for CO2 sequestration,” *Applied Thermal Engineering*, vol. 33-34, pp. 144–156, Feb. 2012. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1359431111005114

[68] Sverre Overå, “EL001 Northern Lights - Mottak og permanent lagring av CO2,” 2019. [Online]. Available: https://norlights.com/wp-content/uploads/2021/03/EL001-Northern-Lights-Impact-Assessment-October-2019-Norwegian.pdf

[69] R. Neerup, V. E. Rasmussen, S. H. Vinjarapu, A. H. Larsen, M. Shi, C. Andersen, K. Fuglsang, L. K. Gram, J. Nedenskov, J. Kappel, P. Blinksbjerg, S. Jensen, J. L. Karlsson, S. Borgquist, J. K. Jørsboe, S. N. Villadsen, and P. L. Fosbøl, “Solvent degradation and emissions from a CO2 capture pilot at a waste-to-energy plant,” *Journal of Environmental Chemical Engineering*, vol. 11, no. 6, p. 111411, Dec. 2023. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2213343723021504

[70] E. E. . R. Energy, “GREET.” [Online]. Available: https://www.energy.gov/eere/greet

[71] G. Delta, "openLCA Nexus: The source for LCA data sets." [Online]. Available: https://nexus.openlca.org/database/ProBas

[72] ——, "openLCA Nexus: The source for LCA data sets. ELCD." [Online]. Available: https://nexus.openlca.org/database/ELCD

[73] ——, "openLCA Nexus: The source for LCA data sets, EcoInvent." [Online]. Available: https://nexus.openlca.org/database/ecoinvent

[74] L. Bilgili, "Comparative assessment of alternative marine fuels in life cycle perspective," *Renewable and Sustainable Energy Reviews*, vol. 144, p. 110985, Jul. 2021. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S136403212100277X

[75] M. Raynolds, M. D. Checkel, and R. A. Fraser, "Application of Monte Carlo Analysis to Life Cycle Assessment," *SAE Transactions*, vol. 108, pp. 1–9, 1999, publisher: SAE International. [Online]. Available: https://www.jstor.org/stable/44650581

[76] R. Chen, Z. Qin, J. Han, M. Wang, F. Taheripour, W. Tyner, D. O'Connor, and J. Duffield, "Life cycle energy and greenhouse gas emission effects of biodiesel in the United States with induced land use change impacts," *Bioresource Technology*, vol. 251, pp. 249–258, Mar. 2018. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0960852417321648

[77] Methanol Institiute, "Renewable Methanol." [Online]. Available: https://www.methanol.org/renewable/

[78] Directorate-General for Climate Action (European Commission), *Going climate-neutral by 2050: a strategic long term vision for a prosperous, modern, competitive and climate neutral EU economy.* Publications Office of the European Union, 2019. [Online]. Available: https://data.europa.eu/doi/10.2834/02074

[79] "Carbon Capture and Storage in the United States | Congressional Budget Office," Dec. 2023. [Online]. Available: https://www.cbo.gov/publication/59832

[80] MAN Energy Solutions, "Shaft generators for low speed main engines," Apr. 2021. [Online]. Available: https://www.man-es.com/docs/default-source/marine/tools/5510-0003-03ppr.pdf?sfvrsn=b570e4e5_14

[81] IEA, "Is the biofuel industry approaching a feedstock crunch? – Analysis," Dec. 2022. [Online]. Available: https://www.iea.org/reports/is-the-biofuel-industry-approaching-a-feedstock-crunch

[82] Eric C. D. Tan, Troy R. Hawkins, Uisung Lee, Ling Tao, Pimphan A. Meyer, Michael Wang, and Tom Thompson, "Techno-Economic Analysis and Life Cycle Assessment of

Greenhouse Gas and Criteria Air Pollutant Emissions for Biobased Marine Fuels," Oct. 2020. [Online]. Available: https://www.maritime.dot.gov/innovation/meta/techno-economic-analysis-and-life-cycle-assessment-greenhouse-gas-and-criteria-air

[83] T. Solakivi, A. Paimander, and L. Ojala, "Cost competitiveness of alternative maritime fuels in the new regulatory framework," *Transportation Research Part D: Transport and Environment*, vol. 113, p. 103500, Dec. 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1361920922003261

8 Appendix

Appendix 1: Methanol Calculation from GREET

Captured CO_2 used in eMeOH production is modeled based on the pathway found in the GREET database. GREET allows for eight different point-source pathways of captured CO_2.

1. ethanol refinery
2. ammonia plant
3. natural gas processing plant
4. hydrogen steam-methane reforming (SMR)
5. cement plant
6. steel plant
7. natural gas combined cycle (NGCC) power plant
8. coal power plant

The above options will be mixed according to the current spread of facilities in the US and weighed against the capacity for each sector.

Table 10: Share of captured CO_2 based on industry USA

Source	Market share
Electric	6.28%
Ethanol	8.07%
H	4.04%
NG	61.88%
NH3	19.73%

Table 11: CCS facilities in the USA (2023) [79]

Facility Name	Type	CO2 captured [Mt/year]	CO2 captured [%]
Terrell	NG	0.5	2.24%
Enid Fertilizer	NH3	0.2	0.90%
Shute Creek	NG	7.0	31.39%
Great Plains	NH3	3	13.45%
Arkalon	Ethanol	0.5	2.24%
Century Plant	NG	5	22.42%
Bonanza BioEnergy	Ethanol	0.1	0.45%
Core Energy	NG	0.4	1.79%
Air Products	H	0.9	4.04%
Coffeyville	NH3	0.9	4.04%
Lost Cabin	NG	0.9	4.04%
PCS Nitrogen	NH3	0.3	1.35%
Petra Nova	Electric	1.4	6.28%
Illinois Industrial	Ethanol	1	4.48%
Red Trail Energy	Ethanol	0.2	0.90%
Total production		22.3	100.00

Appendix 2: Energy Demand Calculations

The Matlab code was used to determine if an afterburner would be necessary. The software later calculates the specific values for both the reboiler and the afterburner using the formulas and syntax presented below.

```
%%
r = 0.7;                %Capture rate
alpha = -0.5659;
beta = 0.1603;
Pfeed = 1;
q=[41.2, 19.9, 37, 37.4]'; %Lower heating values for all fuels
x_CO2 = [0.052, 0.11, 0.052, 0.052]';
Eb = (alpha * log(Pfeed*x_CO2.*(1-r)^beta) + 2.453)*r   % Boiler duty

eta_e = 0.5;    %Engine efiiciency
eta_w = 0.25;   %Ammount of usable waste heat

x_C = [0.85, 0.62, 0.77, 0.78]'; %Carbon content in each fuel
C_to_CO2 = 3.67;        %C to CO2 factor

Ee = q*(1-eta_e)*eta_w/(x_C*C_to_CO2) % MJ / kgCO2inToCCS aka kgCO2outOfEngine

Ea = Eb - Ee    %After burner load
```

Appendix 3: Process Diagrams from OpenLCA

All of the process diagrams shown are taken from the modeling done in OpenLCA. The specific parameter values in the image does not represent reality as the software computes several of the values at execution of the LCIA.

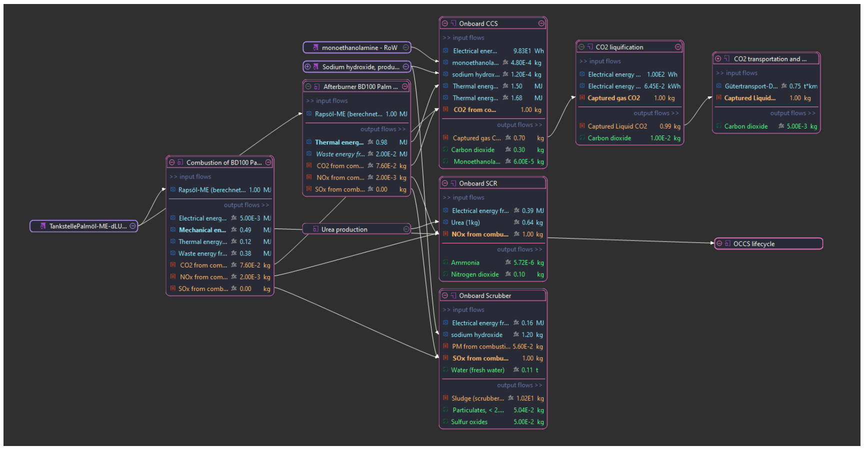


Figure 34: BD100 Palm oil process diagram OpenLCA

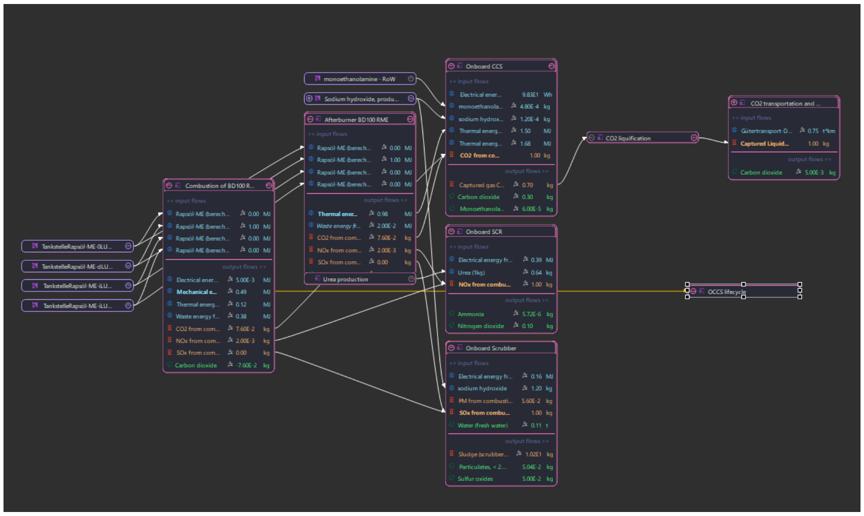


Figure 35: BD100 RME Process diagram OpenLCA

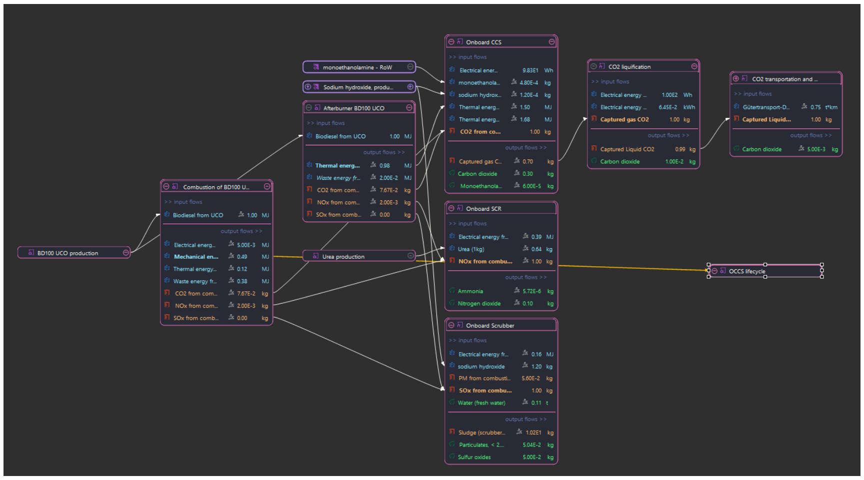


Figure 36: BD100 UCO process diagram OpenLCA

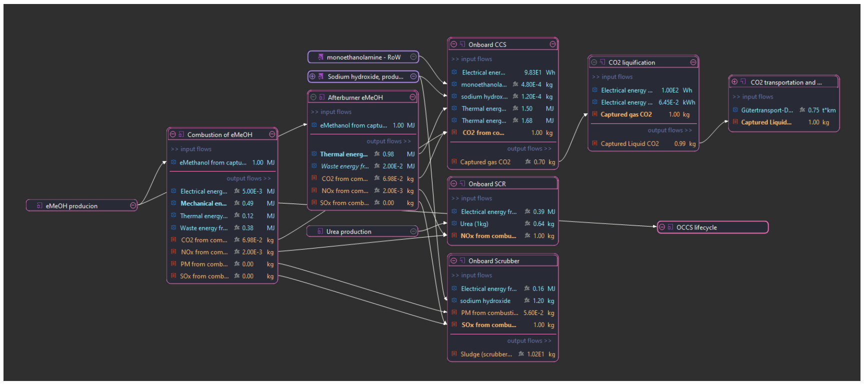


Figure 37: Green Methanol process diagram OpenLCA

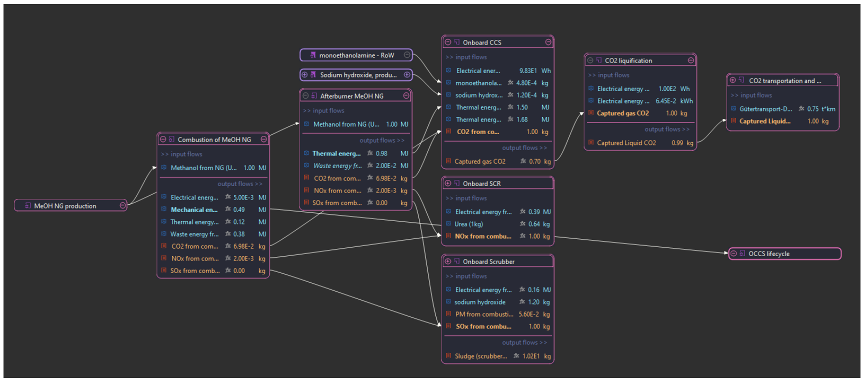


Figure 38: NG Methanol process diagram OpenLCA

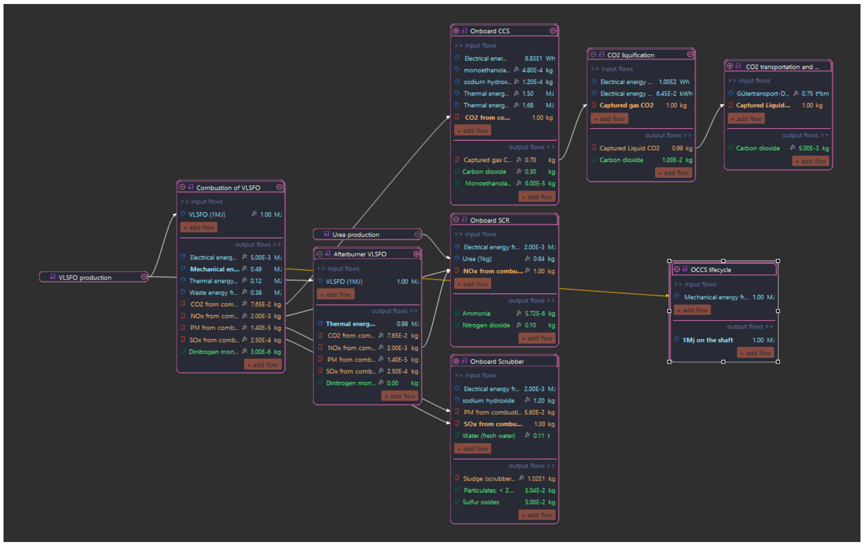


Figure 39: VLSGO process diagram OpenLCA

Appendix 4: Stoichiometric Fuel Calculations

Table 12: Calculations to determine fuel parameters

Methanol	CH3OH	O2	O2 luft	N luft	CO2	H20	O22	N
mol	2	3	3	12	2	4	0	12
g/mol	32.4	32	32	14	44	18	32	14
g	64.8	96	96	168	88	72	0	168
Percentage					0.111111111	0.222222222	0	0.666666667

Table 13: Calculations to determine certain fuel parameters [40]

		FAME type	C	H	O	C	H	O	C	H	O	kg/kg fuel	LCV	kg/kJ in fuel
UCO	mono unsatturated	19:1	20	38	2	240	38	32	77.4%	12.3%	10.3%	2.84	37	76.72
Rapeseed / Soy	polly unsatturated	18:2	19	34	2	228	34	32	77.6%	11.6%	10.9%	2.84	37.4	76.03
Tallow	satturated	18:0	19	38	2	228	38	32	76.5%	12.8%	10.7%	2.81	37	75.82