CHALMERS
UNIVERSITY OF TECHNOLOGY

Setting a course to a greener future

Life-cycle Assessment of General Cargo Ships under 5,000 GT and the regulatory compliance with the FuelEU maritime regulation

Master’s Thesis in Circular Economy

Linda Segerer

DEPARTMENT OF MECHANICS AND MARITIMES SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2024
www.chalmers.se

Abstract

To mitigate emissions and negative environmental impacts from maritime transportation, a transition to climate-friendly fuels and propulsion systems is necessary. The FuelEU maritime regulation aims to facilitate this transition, but currently excludes ships below 5,000 GT. Additionally, there's limited understanding of the environmental impact of general cargo ships, particularly smaller vessels below 5,000 GT. This study investigates the life-cycle performance of small general cargo ships with three different propulsion systems and assesses their potential compliance with the FuelEU maritime regulation. A well-to-wake attributional life-cycle assessment of one model general cargo ship (> 5,000 GT) with three different propulsion systems is conducted. The different propulsion systems are marine gas oil (Case 1), electro-methanol (Case 2) and battery-electric (Case 3). Four phases of the ship and its fuel are considered: (1) shipbuilding phase; (2) ship operation; (3) ship maintenance and replacements and the (4) fuel life-cycle. Case 3 is excluded from the results because it was considered technically infeasible. The compliance with the FuelEU maritime regulation was assessed by estimating the minimum share of eMeOH necessary to meet the required emission reduction targets. The LCA results show that Case 2 resulted in a better life-cycle performance for most impact categories compared to Case 1. The operational and fuel production phases had the most significant life-cycle impact. Sensitivity analysis highlighted the influence of the fuel production pathway, especially the carbon intensity of electricity for producing methanol in Case 2. The analysis of the FuelEU maritime regulation showed the minimum shares of eMeOH necessary to comply with the required emission intensities, starting from 2% in 2025 to 97% in 2050. In addition, concerns were raised about missed opportunities for emissions reduction and maritime innovation by excluding ships below 5,000 GT from this regulation. The study shows that eMeOH powered general cargo ships (< 5,000 GT) have potential to reduce the life-cycle impacts associated with maritime transport and suggests adjustments to the FuelEU maritime regulation to include general cargo ships (< 5,000 GT) for more effective emission reduction. Future research should explore broader implications of excluding ship below 5,000 GT from regulations and improve data availability for general cargo ships to provide a more comprehensive understanding of their environmental impact and policy effectiveness.

Keywords: Life-cycle assessment, General cargo ships, electro-Methanol, FuelEU maritime regulation

Acknowledgment

I would like to express my heartfelt gratitude to the following individuals and organizations who have made this research possible:

First and foremost, I would like to thank IVL - Swedish Environmental Research Institute for their collaboration. As an independent, non-profit research organization owned by a foundation established by the Swedish government and industry, IVL plays a crucial role in the development of solutions to environmental problems at both national and international levels.

I am particularly grateful to Rasmus Parsmo, industrial PhD student at Chalmers and IVL. He is part of the transport and mobility group and granted me the opportunity to join his team and contribute to his research. His collaboration and guidance have been essential to the success of this study.

Last but not least, I would like to thank Dr. Selma Brynolf from Chalmers for her supervision and her thorough feedback. I extend my deepest appreciation to all of the collaborating parties mentioned above for their support, expertise, and commitment to sustainability. Without their involvement, this research would not have been possible

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AC	Acidification
aLCA	Attributional Life-cycle Assessment
BE	Battery-electric
CC	Climate Change
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide Equivalent
CTU	Characterization Toxic Units
DAC	Direct Air Capture
DWT	Dead Weight Tonnage
ECF	Ecotoxicity, freshwater
EEA	European Economic Area
EF	Environmental Footprint v. 3.0 Method
eMeOH	Electro Methanol
EoL	End of Life
EU ETS	European Emission Trading System
EU	European Union
EUF	Eutrophication, freshwater
EUM	Eutrophication, marine
EXIT	Externa kostnader, styrmedel och kostnadseffektiva åtgärder
FU	Functional Unit
GHG	Green House Gas
GT	Gross Tonnage/Tons
HFO	Heavy Fuel Oil
HTc	Human Toxicity (cancer effects)
HTnc	Human Toxicity (non-cancer effects)
IC	Impact Category
ICE	Internal Combustion Engine
IMO	International Maritime Organization
LCA	Life-cycle Assessment
LCC	Life-cycle Costing
LCIA	Life-cycle Impact Assessment
LCV	Lower Calorific Value
LDT	Light Displacement Tonnage
LFO	Light Fuel Oil
LNG	Liquefied Natural Gas
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MRV	Monitoring, Reporting and Verification
NM	Nautical Miles
NO_X	Nitrogen Oxides
OD	Ozone Depletion
PMM	Propulsion Machinery Mass
POF	Photochemical ozone formation
PSV	Propulsion Machinery Volume
RFNBO	Renewable Fuel of Non-Biological Origin
RUF	Resource use, fossil
RUM	Resource use, minerals and metals

SCR	Selective Catalytic Reduction
SO_X	Sulfur Oxides
SSE	Shore-side Electricity
TtW	Tank-to-Wake
VOCs	Volatile Organic Compounds
WtT	Well-to-Tank
WtW	Well-to-Wake

1. Introduction

1.1 Background

Maritime transportation plays a crucial role in worldwide trade and the economy. Within the European Union (EU), it facilitates 77% of external trade and 35% of intra-EU trade (EMSA & EEA, 2021). Shipping is one of the most energy-efficient modes of transportation and the industry contributes significantly to the economic and social well-being of the EU. However, it also poses environmental and health challenges to EU citizens. Ship traffic in the European Economic Area (EEA) accounts for 13.5% of all Union GHG emissions from transport. Further, maritime transport is projected to increase globally in the next decades, leading to increasing GHG emissions from about 90% of 2008 emissions in 2018 to 90-130% of 2008 emissions by 2050 (EMSA & EEA, 2021). This poses challenges to the EU goal of being climate neutral by 2050 (Regulation (EU) 2021/1119).

To achieve a reduction in GHG emissions, a shift towards ships powered by climate-friendly fuels and propulsion systems is required. To support this transition, the European Parliament and European Council agreed on several directives and regulations governing emission reduction in the shipping sector. Since 1 January 2018, large ships (> 5,000 gross tons (GT)) loading or unloading cargo or passengers at ports in the EEA must monitor and report related GHG emissions (currently only CO_2 emissions, but N_2O and CH_4 emissions starting from 1 January 2024) and other relevant information in conformity with the "Monitoring, reporting and verification (MRV) Maritime Regulation" (Regulation (EU) 2015/757). As part of the "fit for 55" package and the European Green Deal, the FuelEU maritime regulation aims to support the uptake of sustainable maritime fuels by limiting the carbon intensity of the energy used on board ships (Regulation (EU) 2023/1805). In summary, the proposal sets a fuel standard for ships above 5,000 GT and introduces a requirement for the most polluting ship types to use onshore electricity when at berth. Hereby it puts the responsibility for compliance on the shipping company. The most recent legislative change in January 2024 was the extension of the EU's Emissions Trading System (EU ETS) to cover CO_2 emissions from all large ships (> 5,000 GT) entering EU ports, regardless of their flag (Regulation (EU) 2023/957).

When looking at the current legislation governing maritime transport in Europe, it stands out that vessels below 5,000 GT are currently excluded. Only for the MRV Maritime regulation is it planned to include emissions from offshore ships and general cargo ships between 400 – 5,000 GT, starting from 1 January 2025 (Regulation (EU) 2023/957). Yet, according to a study by Transport & Environment (2022), ships under 5,000 GT operating in Europe emit a total of 19.7 $MtCO_2$, which corresponds to 15% of the total emissions of all ships under the proposed geographical scope of the EU ETS. It has been shown that ships with a gross tonnage just below the 5,000 threshold have higher average emissions and engine propulsion power compared to those just above the threshold (Transport & Environment, 2022). This reveals a lack of regulatory coverage for emissions from ships below 5,000 GT in the existing maritime legislation in Europe. In the context of Europe's goal of being climate neutral until 2050, this poses the question of the relevance of the environmental impact of this exclusion.

Research that analyses the environmental impact of different types of ships focus mostly on, for example, container ships (Gilbert et al., 2017), RoPax ships (Kanchiralla et al., 2022; Kanchiralla et al., 2023; Seithe et al., 2020), bulk carriers (Dong & Cai, 2019; Quang et al., 2020), tankers (Bicer & Dincer, 2018; Kanchiralla et al., 2022; Quang et al., 2021), cruise vessels (Seithe et al., 2020) or service vessels (Kanchiralla et al., 2023). Thus, little knowledge is available about general cargo ships. This is supported by the review of Mondello et al. (2023) who discovered that fishing vessels, cargo ships, recreational ships, and bulk carriers were the most widely investigated ship types among the LCA and LCC studies reviewed, in which the type of ship was specified. In addition, in the report “Climate Impacts of Exemptions to EU’s Shipping Proposals” by Transport & Environment (2022), general cargo ships were not even specified as their own category. Furthermore, in the review by Mio et al. (2022) summarizing LCA outcomes in the maritime sector, general cargo ships were not specified as their own category either. In contrast, only Zhang et al. (2022) and Brynolf et al. (2023) analyzed the environmental impact of general cargo ships. However, Zhang et al. (2022) only for those constructed in China between 2011 and 2015 and Brynolf et al. (2023) for an average general cargo ship representative for Nordic shipping. Thus, this literature review revealed a gap in scientific knowledge about general cargo ships and the quantification of their environmental impact.

In summary, the research gap identified in existing maritime transport legislation in Europe concerns the exclusion of ships of less than 5,000 GT, a category that contributes significantly to emissions according to Transport & Environment (2022). This regulatory gap raises questions about the effectiveness of the current measures, particularly in terms of achieving emission reduction targets. In addition, there is a general lack of knowledge regarding the environmental impact of general cargo ships, as the existing literature tends to focus on other types of ships, meaning that environmental impact of general cargo ships is not well researched.

1.2 Aim of the Thesis

This study aims to contribute to the previously defined knowledge gap by analyzing the life-cycle performance of small general cargo ships (< 5,000 GT) with three different propulsion systems, representing small transport ships. This thesis is part of the project “Externa kostnader, styrmedel och kostnadseffektiva åtgärder” (EXIT) at IVL. The EXIT project aims to carry out an overall assessment of European shipping's emissions of air pollutants and greenhouse gases as well as emissions affecting the marine environment. This thesis relates to the sub-objective of evaluating the external costs of shipping in terms of effects on human health, climate and the marine environment. The main research question explored in this study is:

RQ1: What is the life-cycle performance of general cargo ships (< 5,000 GT)?

The following sub-research questions aim to address more concrete aspects of the environmental impact of general cargo ships below 5,000 GT and their interaction with European legislation and emission reduction potentials.

RQ2: What are the main challenges and opportunities for general cargo ships (< 5,000 GT) in terms of improving their life-cycle performance?

RQ3: How does the selected model general cargo ship and the general cargo ships of the Swedish fleet comply with the FuelEU maritime regulation?

1.3 Structure of the Thesis

To adequately answer the research questions, this report is divided into several parts. Chapter 2 provides background information on the general cargo ship segment and the alternative propulsion systems investigated in this study. Chapter 3 presents the goal, scope, functional unit and limitations of the assessment. Chapter 4 then provides detailed information on the data collection, together with the quantification of the life-cycle inventory. This is followed by a results section (Chapter 5), which includes the interpretation of the characterization results, contribution analyses and sensitivity analysis as well as the policy assessment. Chapter 6 provides an in-depth discussion of the results and Chapter 7 concludes the report with a summary of the results and recommendations for future research.

2. General Cargo Ships and Alternative Propulsion Systems

This chapter describes the general cargo ship segment with a focus on vessels of less than 5,000 GT. In addition, a description of the alternative propulsion systems used in this study is given.

2.1 General Cargo Ship Segment

According to the International Maritime Organization (IMO), general cargo ships are ships "with a multi-deck or single-deck hull designed primarily for the carriage of general cargo" (IMO, 2019). A general cargo ship is a type of ship that is designed to carry a variety of different types of cargo. Unlike specialized ships that are designed to carry only one type of cargo, such as tankers or container ships, general cargo ships are versatile and can carry a wide range of goods. These vessels can be either geared or ungeared, meaning they have on-board cranes for loading and unloading. General cargo ships come in various sizes, from small coastal vessels to large ocean-going vessels. Some of the largest general cargo ships can carry up to 30,000 tons of cargo, while smaller ships usually carry between 1,000 and 5,000 tons (Ratson Shipbuilding, 2023). In 2023, 1,475 ships were classified as general cargo in Europe, representing around 10% of the world's general cargo fleet, with an average age of around 22 years in European ownership and 29 years in non-European ownership (view Figure 1) (EMSA, 2023).

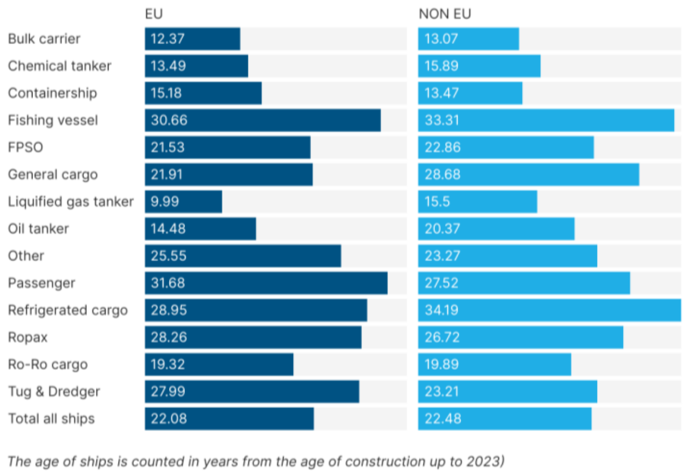


Figure 1: Age of ships by ownership in EU. Source: EMSA (2023).

Looking at the lifetime of the smaller general cargo vessels (0 - 5,000 dwt), it is noticeable that this segment consists of a very old fleet compared to the larger general cargo vessels (> 5,000 dwt) and other vessel segments, with an average lifetime of around 37.5 years as shown in Table 1 (S&P Global, 2024a). According to the Swedish port call data for 2022, most of the general cargo vessels (< 5,000 GT) were built between 2006 and 2009 (Styhre et al., 2024). This means that they will most likely still be in operation for the next 20 years.

Table 1: Average lifetime of general cargo ships categorized by dead weight tonnage (dwt). Source: Styhre et al. (2024) & S&P Global (2024a).

dwt [t]	Average Lifetime [yr]	Number of Vessel [#]	Average dwt [t]
0 – 5,000	37.5	295	2,200
5,000 – 10,000	31.2	84	6,876
10,000 – 20,000	26	32	12,800
> 20,000	26	44	31,700

Looking at the routes of this segment, the variability of the routes in terms of their lengths is apparent, starting from 2 nautical miles (nm) to over 5,953 nm for one trip (Styhre et al., 2024). However, as shown in Figure 2, most routes are shorter than 500 nm with a median of 300 nm and a mean of 407 nm. Looking at the distribution of the size measured in GT of general cargo ships (< 5,000 GT) from Swedish Port Call data in 2022, a high variability is observable as well (view Figure 3). The median of the size is 2,999 GT and the mean is 3,061 GT. In contrast, the distances between ports of general cargo ships larger than 5,000 GT show that in absolute numbers, they call ports less often than the smaller general cargo ships (view Appendix A.1). However, the smaller and larger general cargo ships have a similar distribution of length of routes. Moreover, the distribution of size measured in GT of general cargo ships larger than 5,000 GT reveals that most of these ships are approximately between 5,000 to 10,000 GT (view Appendix A.2). In contrast, this suggests that general cargo ships below and above 5,000 GT are primarily differentiated by their size, yet travel on similar routes.

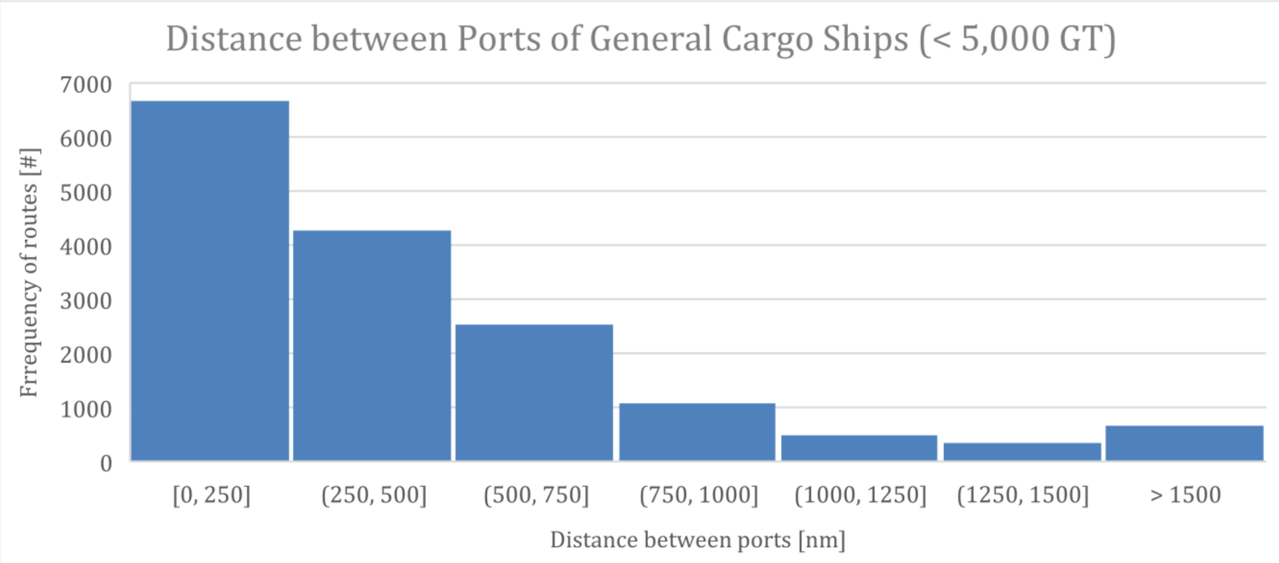


Figure 2: Distribution of distances between ports of general cargo ships (< 5,000 GT). Source: Styhre et al. (2024) & S&P Global (2024a)

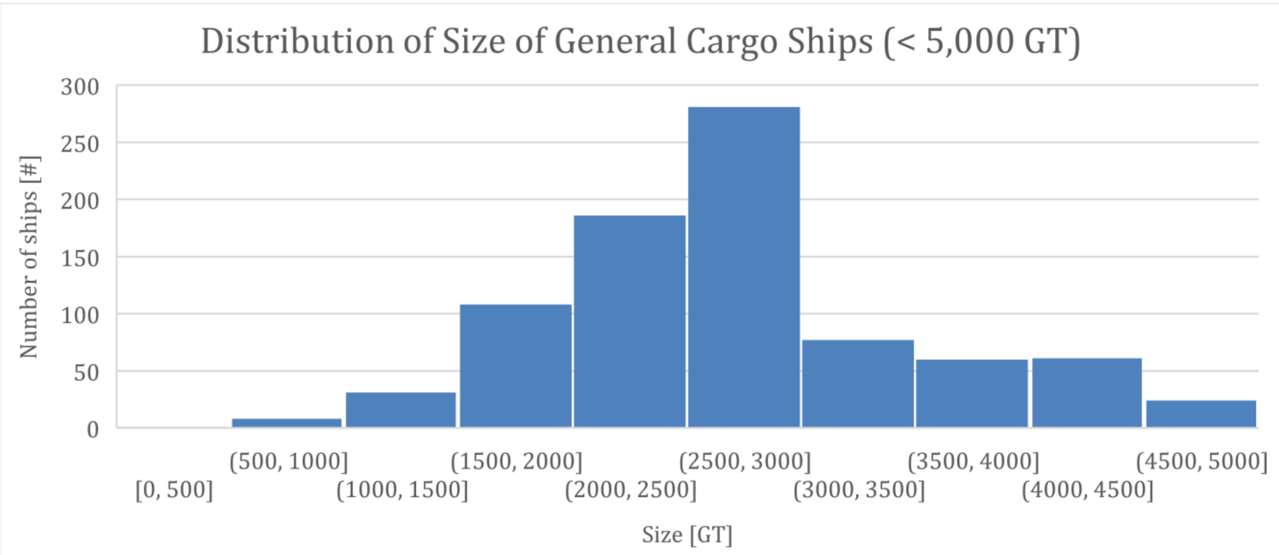


Figure 3: Distribution of size of general cargo ships (< 5,000 GT). Source: Styhre et al. (2024) & S&P Global (2024a)

In summary, the general cargo ship segment (< 5,000 GT) is characterized by its high variability in terms of size and route length. In addition, this segment stands out due to its long lifetime compared to other vessel segments. Although general cargo ships (< 5,000 GT) are not currently covered by most European and international regulations, these ships will need to change to achieve full decarbonization of the shipping sector based on their long lifetime and play an important role for Swedish ports. Next, the two alternative propulsion systems used in this study are described.

2.2 Alternative Propulsion Systems for General Cargo Ships

Currently, ships are mainly powered by fossil fuels like heavy fuel oil (HFO), marine diesel oil (MDO), or marine gas oil (MGO). Their combustion in the ship engine results in a large amount of harmful emissions, such as nitrogen oxides (NO_X), sulfur oxides (SO_X) particulate matter (PM) and other GHGs (Ait Allal et al., 2019). Among several studies analyzing potential alternative propulsion systems and fuels, methanol (MeOH) and electrification are promising solutions (Kanchiralla et al., 2022; Korberg et al., 2021; Perčić et al., 2024).

Among zero-carbon powering options, electrification represents an available technology that has already been studied and applied in the shipping sector (Kanchiralla et al., 2022; Perčić et al., 2020; Perčić et al., 2024). Three types of electrified ships use batteries: hybrid ships, plug-in hybrid ships and all-electric ships. Plug-in hybrids and hybrid ships usually combine a diesel engine with a battery, while an all-electric ship is a ship that is powered solely by a battery. Especially all-electric ships offer high emission reduction potential when charged with renewable electricity (Jeong et al., 2020). One of the limitations of using batteries alone to power ships is the distance the ship can travel, i.e., the range of a voyage, which depends on the energy density of a battery. Due to the limited space available to store enough batteries to power the ship on a long-distance voyage, full electrification is usually limited to ships operating close to the coast. Another limitation is the high investment cost, which depends on the size of the battery and the market, i.e., the current price of the battery (Korberg et al., 2021; Perčić et al., 2024).

In contrast, methanol is a well-known alternative fuel that can be used today and is expected to have increased production in the future (Harahap et al., 2023). Especially in the short-term (now to 2030), methanol offers a low-carbon alternative to conventional fuels (Wang et al., 2024). Methanol as a fuel can power fuel cells and internal combustion engines (Li, Jia, Wang, Wang, Negnevitsky, Hu, et al., 2023; Li, Jia, Wang, Wang, Negnevitsky, Wang, et al., 2023). It can be produced from biomass, biomethane, renewable electricity and CO_2, as well as from fossil sources such as natural gas and coal. Most methanol is currently produced from natural gas (IRENA, 2021; Methanol Institute, 2023). Renewable e-methanol is of particular interest to the marine sector as it is one opportunity for decarbonizing the maritime shipping industry (Harahap et al., 2023). The main constraint on the production of renewable e-methanol is the availability and cost of a supply of CO_2 that is not derived from fossil fuels and renewable electricity. Methanol as a maritime fuel requires little or no engine modification and can deliver significant carbon emission reductions compared to conventional fuels (IRENA, 2021). Utilizing methanol as a shipping fuel benefits from a well-established transportation and distribution infrastructure. Furthermore, methanol bunkering does not require special storage, as the fuel is compatible with fossil liquid fuels and methanol is liquid at ambient pressure and temperature (IRENA, 2021). Even though that methanol has a higher energy density than liquefied natural gas (LNG), ammonia or hydrogen, it still is lower than that of traditional marine fuels. For example, the energy density of MGO is 2.4 times higher than for methanol meaning that storage and fuel tanks on a methanol-fueled ship take up about 2.4 times more space than on a ship using MGO (Methanol Institute, 2023). Once well-to-wake (WtW) emissions are included, e-methanol (eMeOH) is among the shipping fuels with the lowest emissions (Brynolf et al., 2023; Methanol Institute, 2023).

BE and eMeOH powered ships represent two different and relevant alternative propulsion systems. Thus, the alternative decarbonization solutions selected are a full-electric powered and an electro-methanol in an internal combustion engine (ICE) powered general cargo ship (<

5,000 GT). In contrast, also the conventional MGO-powered general cargo ship (< 5,000 GT) is analyzed as a baseline scenario.

3. Methodology

The present study's main objective is to analyze the life-cycle performance of general cargo ships (< 5,000 GT). Thus, Life-Cycle Assessment (LCA) was considered an appropriate research tool. LCA is a standardized method that allows the assessment of the potential environmental impacts of a product, process, or service throughout its entire life-cycle, from raw material extraction and processing, through manufacturing, transport, use and final disposal (ISO, 2006). This chapter describes the LCA methodology and the selected case study ships.

3.1 Goal and Scope Definition

This section provides the intended application of this LCA. In addition, the type of LCA, the temporal, geographical, technological coverage and the functional unit according to the ILCD handbook and ISO standards are specified (ILCD, 2010; ISO, 2006). The main intended application of this LCA is the identification of opportunities to improve the life-cycle performance of general cargo ships (< 5,000 GT) at various points in their life-cycle. Additionally, it informs decision-makers in industry, governments, or non-government organizations about the life-cycle performance of general cargo ships (< 5,000 GT). Further, the LCA results are used to evaluate the FuelEU maritime regulation. For academia, this LCA contributes to building knowledge about general cargo ships (< 5,000 GT). Moreover, it contributes to the EXIT project at IVL. Next, the type of LCA is described.

3.1.1 Attributional Life-cycle Assessment

While consequential LCA is valuable for understanding the consequences of change of the assessed product or system, attributional LCA provides a more comprehensive picture of the current environmental impact (ILCD, 2010). This aligns with the research objective of assessing the environmental impact of general cargo ships (< 5,000 GT). Therefore, attributional LCA (aLCA) was selected. According to the ILCD handbook (2010), aLCA refers to the modelling principle that depicts the potential environmental impacts that can be attributed to a system (e.g. a product), in this case the model ships, over its life-cycle. Attribution modeling is based on historical, evidence-based, quantifiable data with known (or low) uncertainties. It includes all processes that are considered significant for the system under investigation. In attribution modeling, the system is represented as it currently exists, existed in the past or is predicted to exist in the future (ILCD, 2010). This entails that the situation under current demand is modelled, with the aim of providing a snapshot of the environmental performance of the system without considering broader system-level effects or potential changes in consumption patterns or market dynamics (Guinée, 2002).

3.1.2 Scope and Boundaries

In this study, a well-to-wake attributional LCA of one model general cargo ship (> 5,000 GT) with three different propulsion systems is conducted. The different propulsion systems are (i) marine gas oil, (ii) electro-methanol and (iii) battery-electric. In this system boundary, four phases of the ship and its fuel are considered: (1) shipbuilding phase, including the material and energy consumption of building the ship; (2) ship operation; (3) ship maintenance and replacements and the (4) fuel life-cycle. The end-of-life phase is excluded because there is too much uncertainty about future scrapping and recycling technologies due to their long expected lifetime, as described in Chapter 2.1. Furthermore, all three cases are based on the same model general cargo ship. Therefore, their end-of-life treatment is assumed to be comparable and, as such, not meaningful to compare. Components and ships are assumed to be produced in Europe, as well as maintenance and replacement processes. The fuel production is assumed to be located near the port of operation with focus on the Nordic countries and Sweden. The temporal scope of the study is 2022 because data from this point in time is available. The technologies modelled use the most recent data available to accurately represent the present technological state and its current environmental impact. The used technologies and model ships are described in the next Chapter 3.1.3. The geographical scope is northern Europe, with a focus on Sweden because data from Swedish port calls is available. In addition, the geographical scope of focus on Sweden is interesting for this study because Sweden has very ambitious climate policies and the Swedish shipping sector is very active in low-carbon projects and shows strong commitments to decarbonize the shipping sector. Furthermore, Northern Europe has a high potential for renewable maritime fuel production due to their large renewable energy and biomass potential (Harahap et al., 2023). Therefore, this geographical scope is assumed to reflect a realistic case. As a functional unit the "*Operation of a general cargo ship (< 5,000 GT) for one year*" is selected. This FU aims to capture the average yearly life-cycle performance over the lifetime of the ship. Moreover, as an additional functional unit that represents specific ship parameters the "*transport of 1 ton of cargo over 1 nm by sea over the ship's life-cycle*" is chosen. This FU aims to assess the life-cycle performance of the transport work of the ship. Overall, these functional units were chosen to fit the aim of analyzing the life-cycle performance of general cargo ships (< 5,000 GT) and to reveal challenges and opportunities for improving their life-cycle performance. The assessment is performed using the open-source program openLCA. The LCA methodology is summarized in Table 2.

Table 2: Summary of LCA methodology.

Functional unit	(1) Operation of a general cargo ship (< 5,000 GT) for one year (2) Transport of 1 ton of cargo over 1 nm by sea over the ship's life-cycle
Time horizon	2022
Geographical boundaries	Northern Europe, focus Sweden; component manufacturing, electricity generation and fuel production are considered in Europe
Life-cycle phases	Well-to-Wake: (1) shipbuilding phase, (2) ship operation, (3) ship maintenance and replacements, (4) fuel life-cycle

3.1.3 The Model Ship

As a model ship that is retrofitted to the three different cases, the M/S Novomar was selected. This ship was selected because it represents a typical ship operating in Sweden and Northern Europe and its size is in the range of the average size of general cargo ships (< 5,000 GT). As mentioned in 2.1, the average lifetime of general cargo ships (0 – 5,000 dwt) is 37.5 years. Thus, the expected lifetime of these ships, based on their dwt, is 37.5 years. The first model ship – Case 1 – is a conventional MGO-powered general cargo ship and serves as a reference ship. The alternative decarbonization solutions selected are an electro-methanol – Case 2 – in an internal combustion engine (ICE) powered ship and a battery-electric – Case 3 – powered ship. The dimensions of the model ship were taken from the website "Seaweb" of the ship statistic provider S&P Global (2024b) and from the website of the ship operator AtoB@C (2024). The main particulars of the model ship are presented in Table 3.

Table 3: Characteristics of the model ship.

Model ship	M/S Novomar		
	 © hasenpusch		
IMO number [a,b]	9471991	**Length [m]**[a,b]	84.98
GT [t][a,b]	2,984	**Breath [m]**[a,b]	15.2
NT [t][a,b]	1,769	**Draft [m]**[a,b]	5.10
DWT [t][a,b]	4,202	**Cubic capacity [m³]**[a,d]	5,600
LDT [t][a,b]	1,496	**Service speed [knots]**[a]	12
Built [year][a,b]	2008	**Total fuel capacity [m³]**[a]	246
Expected Lifetime [years][c]	37.5	**Installed main engine [kW]**[a,b]	1,800
Propulsion System[a]	4 Stroke Diesel Engine	**Installed auxiliar generator [kW]**[a,b]	4 Stroke 6Cy: 188 kW

[a] Data from Seaweb (S&P Global, 2024a); [b] Data from ship operator AtoB@C (2024); [c] Data from Figure 3;
[d] Secondary data from a similar ship from Seaweb (S&P Global, 2024a).

The decarbonization solutions are taken from Kanchiralla et al. (2022) and adapted to the cases of this study. In the following, the propulsion technologies of the three different cases are described.

Case 1: Ship powered by Marine Gas Oil

Case 1 is the reference case where fossil MGO is fueled in a conventional medium-speed diesel engine with selective catalytic reduction (SCR). The shaft generator and auxiliar engine are required for meeting the auxiliary electrical load. The excess heat from the engine is used with the help of waste heat recovery (WHR) to meet the heat requirement. A normal storage tank is used for storing MGO and its size is based on the fuel capacity of the model ship.

Case 2: Ship powered by electro-Methanol

Case 2 uses eMeOH as its fuel in a dual-fuel engine equipped with SCR, with MGO serving as the pilot fuel. In order to supply the auxiliary electrical load, the shaft generator is necessary. The excess heat from the engine is used with the help of WHR to meet the heat requirement during cruising and maneuvering. The shaft generator is required only to meet the auxiliary electrical load. Normal storage tanks are used for eMeOH and MGO. Since the energy density of MGO is 2.4 times more than for methanol, the fuel tanks on the methanol-fueled ship take up about 2.4 times more space than on a ship using MGO (Methanol Institute, 2023). The size of the storage tanks is based on the fuel capacity of the model ship M/S Novomar. As methanol is characterized by a low cetane number which reduces the self-ignition quality, a small amount of pilot fuel is required. The amount of pilot fuel required is assumed to be 5% of the energy content (Man Energy Solutions, 2021).

Case 3: Ship powered by Battery-electric

For the BE ship, the electricity is stored in NMC811 batteries and used for the ship operation and is charged using electricity from the port, assuming the necessary charging infrastructure exists. The battery is sized for a maximum distance of 1,000 nm with a reserve capacity of 60%. Power is managed using the control unit and is directly used for electrical propulsion, heat pump, and auxiliary loads.

A simplified description of the fuel production pathways, the propulsion system configuration and component manufacturing are shown in Figure 4.

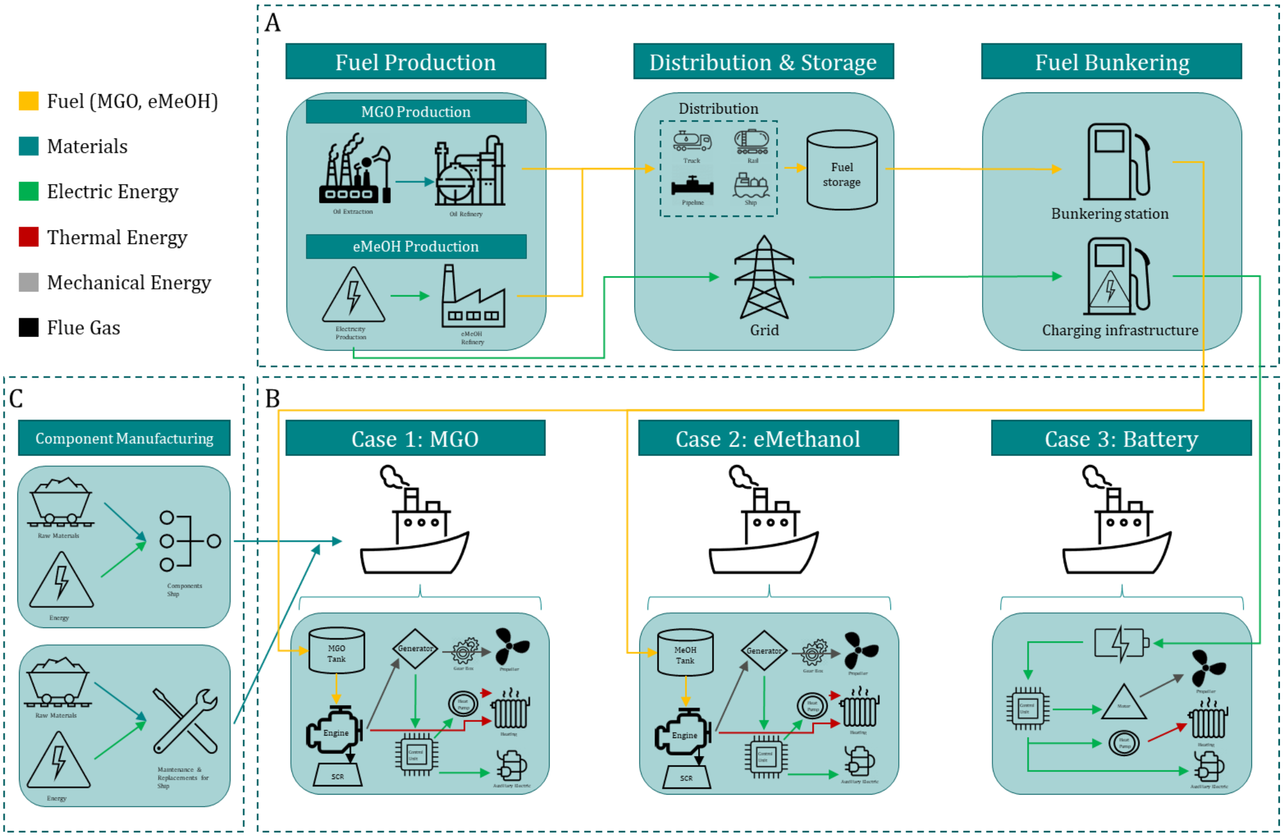


Figure 4: A = Fuel Production Pathways; B = Propulsion System Configurations; C = Component Manufacturing. Adapted from Kanchiralla et al. (2023).

3.1.4 Limitations and Assumptions

The limitations and assumptions of this study are outlined as follows. The assessment is performed from the point of view of the shipping sector. The system boundary is defined around the ship and focuses on the main parts of the ship and its power system. Other ship components such as gear, crew, transported goods and port operations are not considered. Furthermore, the model only evaluates the life-cycle performance at a specific time point (2022) and does not account for secondary or tertiary feedback loops. This study is limited by the lack of available and high-quality data on technical performance, emission profiles and material demand for the assessed model ships. Therefore, the following assumptions were made: (1) for the ship building phases, only the material production of the components is considered, due to a lack of information; (2) regarding the infrastructure necessary to refuel the ships, it is assumed that it is sufficiently developed; (3) The energy demand of the ship remains the same, although there may be a higher fuel consumption for Case 2 due to the larger tanks, and is derived from the MRV data. Furthermore, the cost of the different alternatives is not assessed due to the limited timeframe of the study, despite it being one of the main adoption criteria. Moreover, although safety is a crucial factor in designing alternative power systems, especially with methanol's toxicity to humans (Methanol Institute, 2023), it was not considered in this study. Lastly, as explained in Chapter 3.1.2 the EoL is not included.

3.1.5 Impact Assessment Method and Categories Assessed

This study uses the 'Environmental Footprint v. 3.0 Method' (EF) impact assessment family, in recognition of the European Commission's efforts to improve the comparability of LCA results. This method takes a midpoint approach. This means that the EF impact category (IC) indicators quantitatively represent environmental damage (i.e. effect) caused by a specific human activity (i.e. cause). As EF does not further include damages caused by these effects it reduces uncertainties. Additionally, it allows a higher number of impact categories and the results are more accurate and precise compared to the three areas of protection commonly used at the endpoint level (ILCD, 2010). A midpoint approach was thus found most appropriate for the present study following similar studies like Kanchiralla et al. (2023) or Kanchiralla et al. (2022). This report focuses on twelve EF impact categories (view Table 4), namely climate change, ozone depletion, particular matter, photochemical ozone formation, acidification, eutrophication (marine), eutrophication (terrestrial), human toxicity (cancer effects), human toxicity (non-cancer effects), ecotoxicity (freshwater), resource use (minerals and metals) and resource use (fossils). They were chosen, and used by several other authors (Kanchiralla et al., 2022; Kanchiralla et al., 2023; Malmgren et al., 2021), because they best reflect the environmental concerns of the maritime sector. The total impact of the impact categories is given by:

$$IRc = \sum_{s} CFcs * Ms$$

where the indicator result (IR_c) is characterized by the characterization factor (CF_{cs}) which connects the mass of substance emitted (M_s) with the impact category (c). All emitted substances (s) impacting a specific impact category, as for example climate change, are aggregated into a total number represented by a mass of equivalents (view Table 4).

Table 4: List of impact categories assessed including their acronym, reference unit and a brief description for each. Source: Sala et al. (2017)

Impact Category	Acronym	Reference Unit	Description
Acidification	AC	mol H+ eq.	Refers to the potential acidification of soils and water caused by the release of gases such as nitrogen oxides and sulfur oxides.
Climate Change	CC	kg CO_2 eq.	Refers to the potential global warming due to emissions of GHGs to the atmosphere.
Ecotoxicity, freshwater	ECF	CTU_e	Refers to the impact of toxic substances emitted to the environment on freshwater organisms.
Eutrophication, freshwater	EUF	kg P eq.	Refers to the nutrient-enrichment of freshwater ecosystems due to the release of nitrogen or phosphor-containing compounds.
Eutrophication, marine	EUM	kg N eq.	Refers to the nutrient-enrichment of marine ecosystems due to the release of nitrogen or phosphor-containing compounds.

Human Toxicity (cancer effects)	HTc	CTU_h	Refers to the potential harm caused to human health due to exposure to substances that can induce cancer.
Human Toxicity (non-cancer effects)	HTnc	CTU_h	Refers to the potential harm caused to human health due to exposure to substances that can induce non-cancerous diseases.
Ozone Depletion	OD	kg CFC-11 eq.	Refers to the reduction of the ozone layer in the Earth's stratosphere due to human activities.
Particular Matters	PM	disease incidences	Refers to the suspension of tiny particles in the air causing health and environmental effects. It includes fine particles ($PM_{2.5}$) and coarse particles (PM_{10}).
Photochemical ozone formation	POF	kg NMVOC eq.	Refers to the production of ozone in the Earth's atmosphere through chemical reactions involving sunlight, nitrogen oxides (NO_x), volatile organic compounds (VOCs), and other pollutants. Ozone is a key component of smog and can have significant impacts on human health, ecosystems, and the environment.
Resource use, fossil	RUF	MJ	Refers to the depletion of natural fossil fuel resources.
Resource use, minerals and metals	RUM	kg Sb eq.	Refers to the depletion of natural non-fossil resources.

4. Life-Cycle Inventory

The life-cycle inventory (LCI) corresponds to the "compilation and quantification of inputs and outputs for a given product system throughout its life-cycle" (ISO, 2006). It includes collecting unit process data, addressing multi-functional processes, and calculating the LCI analysis result. In addition, an assessment of the technical viability of the different cases was conducted before calculation the life-cycle impact assessment (LCIA) results.

4.1 Data Collection and Modelling Choices

For the quantification of the system's environmental impacts, the collection of data is necessary. In this study, secondary data was taken from scientific literature and from the LCI database Ecoinvent 3.8. When no data was available proxies or cut-offs were used. Proxies, however, are not very precise as they incorporate data that has not been collected for the process they are representing. The overall system therefore becomes less representative of the real world. Regarding all background processes, data based on the geography of Sweden and (northern) Europe was prioritized when available and global scope was used otherwise. For the inputs, market activities (i.e. labelled as "market for" in Ecoinvent 3.8) were used to represent the consumption mix of a product, linking product-specific suppliers with consumers within a specific geographical area, accounting for transportation and, if relevant, imports and losses as well (Ecoinvent 3.8, 2021). To enhance the reproducibility of this study, all system and unit processes used have been reported in Appendix A.3 – A.6.

4.1 Technical Viability

Before calculating the LCA result, the technical viability of the three cases was assessed. To assess the technical viability of the three cases, the volume and weight ratios of the components of the propulsion system were estimated, following a similar approach as Kanchiralla et al. (2023) and Brynolf et al. (2023). The feasibility of each configuration has been assessed based on the mechanical space available for each vessel, which varies from vessel to vessel. For the feasibility analysis, the mass constraint is assessed based on the dead weight tonnage (dwt) of the ship and the volume constraint is assessed based on the ships gross tonnage (GT). For the mass consideration, the ratio of the mass of the propulsion machinery (including fuel storage and fuel) (PMM) to the dwt is calculated (PMM/dwt) and for the volume consideration, the ratio of the volume of the propulsion machinery (PSV) including tank volume to the GT is calculated (PMV/GT). Case 2 (eMeOH) and Case 3 (BE) were considered infeasible if their mass ratios were more than three times and their volume ratios were more than two times larger than the reference Case 1 (MGO). The parameters used to estimate the volume and weight of the different components when primary data was not available in Seaweb (S&P Global, 2024a), are described in Appendix A.7. Based on these values, the volume and weight of the propulsion systems and the PMM/dwt and the PMV/GT ratios were calculated as displayed in Table 5.

Table 5: The volume and weight of the propulsion systems considered in the study and their feasibility. Green indicates that the case is considered feasible. Red indicates that the case is considered infeasible.

	Case 1 MGO	**Case 2 eMeOH**	**Case 3 Battery**
Volume [m^3]	299	642	778
Weight [tons]	361	511	1911
PSM/DWT	9%	12%	45%
PSV/GT	10%	22%	26%

Based on the results of the feasibility analysis (view Table 5), Case 3 was considered unfeasible because the mass and volume ratios were larger than the cut-off criteria. Thus, Case 3 was excluded for the LCIA results and only a full LCA for Case 1 and Case 2 was conducted. For the volume ratio Case 2 is also slightly above the cut-off criteria. Since Case 2 is retrofitted based on Case 1, there is some uncertainty regarding for example the real-world size of the methanol tank which is assumed to be 2.4 times larger than the tank of Case 1. However, it is questionable whether this factor is applied in real life. In addition, the tank of Case 2 takes up the largest part of the volume. Thus, due to the uncertainty around the size of the tank of Case 2, it is still considered feasible. Next, the inventory analysis for Case 1 and Case 2 are presented.

4.2 Inventory

In the following, the inventory data by life-cycle phases of the model ships are described.

4.2.1 Shipbuilding Phase

In this phase, following the recommendation of Mio et al. (2022), a cradle-to-gate analysis of the vessel itself, including extraction, refinement and transportation of materials and shipbuilding activities, is conducted. In the following the inventory data and assumptions for the main components of the case study ships are described.

Vessel Construction: A baseline model was created for the material composition of the vessel, based on data from Jain et al. (2016) on the materials recovered from the end-of-life stage of a case study ship. Material requirements for the vessel were adjusted based on its light displacement tonnage (LDT).

MGO and eMeOH Engines: The inventory data for the MGO and eMeOH engines is sourced from Ecoinvent 3.8 (market for marine engine | marine engine | Cutoff, U).

Selective Catalytic Reduction: SCR is used to decrease NO_X emissions from fuel combustion. In NO_X SCR, the reduction occurs over a base metal catalyst with ammonia as the reducing agent in reactions that effectively reduce NO_X to N_2 and water. The ammonia is typically supplied from a water solution of urea which is sprayed into the exhaust where the urea decomposes to form ammonia (Brynolf et al., 2014). The typical raw material composition for SCR is used from the study by Jeong et al. (2018).

Alternator: The alternator is used for generating electricity onboard from the engines, the power capacity of the alternator depends on the electrical load. The weight details are calculated from the manufacturing catalog (Siemens, 2018), and the material composition of the electrical generator is taken from the GREET database.

Heat pump: To meet the demand for heating, a heat pump is utilized. The composition of the material used in the study was obtained from the manufacturer's catalog, while the specifications and weight of the material were sourced from Greening and Azapagic (2012).

Tank: For Cases 1 and 2, a fuel tank is required to store methanol and MGO and is assumed to be made of stainless steel. The data used is from Ecoinvent 3.8 (market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S). The size of the tanks is based on the cubic capacity provided by the Seaweb from S&P Global (2024a). The tank size for the methanol ship was adjusted by a factor of 2.4. This is because the energy density of methanol is 2.4 times greater than that of MGO. Therefore, storage and fuel tanks on a methanol-fueled ship require approximately 2.4 times more space than those on a ship using MGO (Methanol Institute, 2023).

Electricity for component production: When not already included in the used datasets, the electricity for the component and vessel production is assumed from the European electricity mix as the components are assumed to be produced in different locations in Europe. The LCI data from IDEMAT 2021 titled "Electricity EU-27" is used.

4.2.2 Ship Operation, Maintenance and Replacements

In the following sections, the assumptions and modeling choices of the operation, maintenance and replacements of the model ships are described.

4.2.2.1 Ship Operation

To ensure the comparability of the two case ships, all ships take the same routes and have the same operational practices (e.g., speed, time at berth, etc.). The ship's emissions during this phase are primarily determined by the type of fuel and fuel consumption, which in turn affects energy consumption. The energy demand of the M/S Novomar was derived by extrapolating the average fuel consumption per dwt of all vessels covered by the MRV regulation, as no primary data was available. The following equation was derived:

$$average\ fuel\ consumption\ per\ dwt = 0.0019 * dwt + 33.398$$

Fuel consumption varies with the engine load and for this study an average main engine load of 80% is assumed. Based on the energy content of the original fuel, the distance travelled per year and the energy conversion efficiencies of the major conversion processes, the energy demands per year of Case 1 and Case 2 were calculated. The tank-to-wake (TtW) efficiencies for both ship propulsion systems is assumed to be 47% (Brynolf et al., 2023). For calculating the results of the additional functional unit of "transport of 1 ton of cargo over 1 nm by sea over the ship's lifetime" a capacity factor of 49% is selected for both cases. The capacity factor was calculated using MRV data. The capacity factor was calculated with the following formula:

$$capacity\ factor = \frac{actual\ average\ tons}{dwt}$$

The "actual average ton" was derived by dividing the total CO_2 emissions by the annual average CO_2 emissions per transport work. In the next step, the median of 49% of all general cargo ships was calculated. However, this value must be treated with caution because the calculation revealed incorrectly reported data with capacity factors exceeding 100%. Therefore, only values below 100% were considered for the calculation used in this study. More details on the capacity factor can be found in Appendix A.8. The main particulars of estimating the energy demand during the operational phase of the ships are displayed in Table 6.

Table 6: Relevant data for ships operation.

	Case 1 MGO	Case 2 eMeOH
Annual average fuel consumption per distance [kg fuel/nm] [a]	41.38	
Lower Heating Value [MJ/kg]	42.7	19.9
Main engine load [%]	80%	
Tank to wake efficiency [c]	47%	47%
Distance [nm/yr] [a]	55,026	
Annual average energy consumption [MJ] [b]	97,231,099.37	
Annual average propeller output [kWh/yr] [a]	12,694,060	
Total fuel consumption per year [kg/yr] [b]	2,277,075	4,641,686
Total pilot fuel (MGO) consumption per year [kg/yr] [b]	-	113,854
Capacity factor [%] [a]	49	

[a] Based on MRV data; [b] adjusted for cases, based on fuel and energy conversion efficiency; [c] Brynolf et al. (2023).

4.2.2.2 Ship Maintenance and Replacements

The following section describes the assumptions and data used for the maintenance and replacements of the major components in the two cases. The ship's SCR catalyst has a lifetime of 13 years and is expected to be replaced three times (Liang et al., 2011). The activating element on the catalyst is assumed as TiO_2 and is around 0.25% of the weight of SCR (Liang et al., 2011). As a proxy for the maintenance processes of the ships, the process of the maintenance of a bulk carrier for dry goods was selected from Ecoinvent 3.8 (maintenance, bulk carrier, for dry goods | maintenance, bulk carrier, for dry goods | Cutoff, U). This is considered appropriate because bulk carriers and general cargo ships are similar in their material composition and structure (Jain et al., 2016).

4.2.3 Fuel Life-Cycle

In the following the inventory data and assumptions for the fuel life-cycles of the case study ships are described.

MGO Production: following the same data selection as Kanchiralla et al. (2022), the production pathway and inventory data for MGO are sourced from Ecoinvent 3.8 (market for diesel, low-sulfur | diesel, low-sulfur | Cutoff, S – Europe without Switzerland). It is assumed that the diesel is produced in Europe.

eMethanol Production: this study uses inventory details from Malmgren et al. (2021) for the production of eMeOH. The process requires CO_2 (1.375 kg/kg MeOH), H_2 (0.189 kg/kg MeOH), electricity (1.98 MJ/kg MeOH), and heat. The CO_2 is captured with a direct air capture (DAC). The CO_2 in this process is considered a negative carbon emission. The heat is provided through electric heating. For the base case, it is assumed that no heat is reused, leading to a total electricity consumption of 5.24 MJ/kg MeOH. It is assumed that the eMeOH is produced in Europe. Renewable energy is used to power the production of eMeOH, with wind power being a common source. Thus, the electricity to produce methanol is assumed to be from wind power. The LCI data for the wind power is from NEED titled “electricity, at offshore wind park 160MW | Scenario: Today” is used.

Urea: the production pathway and inventory data for the urea necessary to run the SCR is sourced from Ecoinvent 3.8 (market for urea | urea | Cutoff, U). It is assumed that the urea is produced in Europe.

The inventory data for the emissions from the combustion of the MGO engine and the methanol dual fuel engine are shown in Table 7. The inventory data was obtained from Kanchiralla et al. (2023). It should be noted that for the MeOH emission inventory data the pilot fuel is also included.

Table 7: Inventory data of emissions from the combustion of MGO and eMeOH. Source: Kanchiralla et al. (2023)

Fuel/Option	**MGO**	**Methanol**
ICE type	4S ICE	4S DF-ICE
Engine load	80%	80%
Fuel consumption (g/kWh)	176	358
Pilot fuel consumption	-	9
NH_3 (g/kWh)	0.05	0.025
BC (g/kWh)	0.005	0.0016
CO_2 (g/kWh)	568	520
CO (g/kWh)	1	0.17
N_2O (g/kWh)	0.03	0.003
CH_4 (g/kWh)	0.01	0.01
NO_x (g/kWh)	2.6	2.6
PM_{10} (g/kWh)	0.4	0.093
SO_x (g/kWh)	0.343	0.017
Formaldehyde (g/kWh)	-	0.0049
Urea required (g/kWh)	9	3.36
Pilot fuel	-	MGO*

* Pilot fuel required is assumed to be 5% of energy content.

5. Results and Interpretation

The aim of this section is to assess and understand the life-cycle performance of the model general cargo ship powered by MGO or eMeOH. This is done by translating the LCI results into their contribution to the selected impact categories, thus making the product systems comparable. The life-cycle impacts are represented in the modelling by impact categories and represented by the results of the system characterization. Furthermore, the results of the LCI and the impact assessment are combined according to the defined goal and scope to draw conclusions and recommendations for general cargo ships (< 5,000 GT). Contribution and sensitivity analyses are carried out to see which processes have the greatest environmental impact, to evaluate the leverage points of the systems studied in terms of improving their life-cycle performance and to assess the robustness of the results. Based on these results, the compliance with the FuelEU maritime regulation concerning emissions and environmental standards for maritime transport is assessed.

5.1 Life-Cycle Impact Assessment Results

In this part, the Life-cycle Impact Assessment (LCIA) results from Case 1 and Case 2 are presented. As argued in Chapter 4.1, Case 3 is excluded from the results because it is considered unfeasible. First, the characterization results of the main FU “Operation of a general cargo ship (< 5,000 GT) for one year” and for the secondary FU “transport of 1 ton of cargo over 1 nautical mile by sea over the ship’s life-cycle" are presented, followed by the contribution and sensitivity analysis. Lastly, challenges and opportunities for improving the life-cycle performance of Case 1 and Case 2 are summarized.

5.1.1 Characterization Results

Characterization, as defined by ISO 14040, is the calculation of the category indicator results. It is used to compare product systems and show their trade-offs by showing the life-cycle impacts of the systems in each category. All characterization, weighted and normalized results of Case 1 and Case 2 can be found in Appendix A.9 and A.10. Figure 5 shows the relative life-cycle performance of the assessed impact categories of Case 1 and Case 2. It is noteworthy that Case 2 (eMeOH) demonstrates a better environmental performance for most of the impact categories assessed except for human toxicity (cancer & non-cancer) and resource use (minerals and metals). Moreover, for the impact categories photochemical ozone formation, marine eutrophication and freshwater ecotoxicity the differences are less than 5%. The paragraphs below provide possible explanations for the results found (next to each impact category’s heading, the system with a higher environmental impact is specified in bold with “Case 1 (MGO)” or “Case 2 (eMeOH)”).

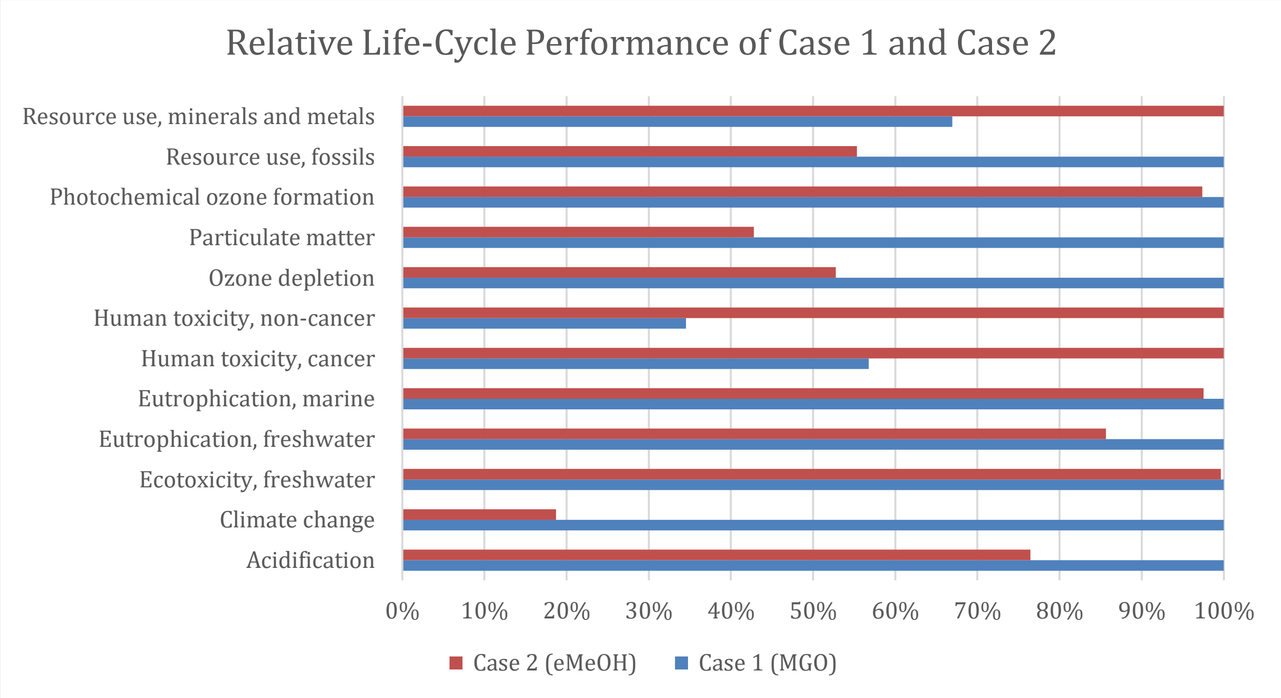


Figure 5: Relative negative environmental impact of Case 1 and Case 2. For numerical details refer to Appendix A.9 & A.10.

Acidification – Case 1 (MGO)

Soil and water acidification are caused by the release of gases such as SO_2, NO_x, and NH_3, as well as an increased concentration of CO_2 in the atmosphere. In the case of ships, these gases mostly come from burning fuels. Additionally, the production of MGO also contributes significantly to the release of these gases. MGO has higher emission factors for most of these gases than methanol (see Table 7) and its production contributes significantly as well. Thus, this results in a higher level of acidification.

Climate Change – Case 1 (MGO)

Similar to acidification, the climate change impact is driven by the release of GHGs into the atmosphere. These gases are primarily emitted during the production and combustion of fuels. MGO, a conventional fuel derived from fossil fuels, contains a higher amount of carbon when burned, and its production is also carbon intensive. Methanol, on the other hand, also emits GHGs when burned. However, as it is assumed to be produced from DAC with renewable energy, the overall emissions are significantly lower. Specifically, the CO_2 emissions from the combustion of MeOH are approximately equal to those captured during the DAC process. Therefore, it is not surprising that the climate change value for Case 2 is only 19% of that for Case 1, mainly driven by the production and combustion of the pilot fuel.

Ecotoxicity, freshwater – Case 1 (MGO)

The ecotoxicity results are mainly affected by the production of MGO and methanol, as well as the construction of the vessels in both cases. In Case 1, the processing of crude oil during the production of MGO emits various pollutants into the air and water, such as heavy metals, sulfur compounds, and volatile organic compounds, which increase the freshwater ecotoxicity. In Case 2, the main contributor to the freshwater ecotoxicity is the infrastructure for the wind park, although to a lesser extent than the pollutants generated during the production of MGO. In Case 2, MGO is only used as a pilot fuel, resulting in similar pollutants contributing to freshwater ecotoxicity but in smaller amounts. Nevertheless, the impact of Case 1 is only marginally higher, at 0.4%, than that of Case 2. This indicates that both systems have a similar impact, but as previously described with different processes driving this impact.

Eutrophication, freshwater – Case 1 (MGO)
Freshwater eutrophication is driven by nutrient enrichment due to the release of phosphorus containing compounds. In both Case 1 and Case 2, shipbuilding, mainly through steel production, the production of fuels and urea are the main processes affecting freshwater eutrophication. The reason why Case 1 is higher than Case 2 could be that Case 1 requires more urea, and the production of MGO emits more kg P eq. in absolute terms compared to the production of methanol.

Eutrophication, marine – Case 1 (MGO)
Marine eutrophication is driven by nutrient enrichment resulting from the release of nitrogen-containing compounds. The main processes that influence the outcome are fuel combustion and, to a lesser extent, fuel production. Ships primarily emit nitrogenous compounds through fuel combustion. When comparing the emission factors for the combustion of MGO and methanol (view Table 7) it is evident that methanol has slightly lower values for N_2O but the same value for NO_x. This leads to the slightly higher results for Case 1 than Case 2, whereby the impact from all other processes like shipbuilding and maintenance and replacements is the same.

Human Toxicity (cancer effects & non-cancer effects) – Case 2 (eMeOH)
Methanol itself is toxic for humans and the environment. Exposure to methanol can result in serious health consequences, including blindness, kidney failure, and in extreme cases, death (Methanol Institute, 2023). In addition, incomplete combustion of methanol may also contribute to human toxicity through possible formaldehyde emissions (Sahu et al., 2023). The higher human toxicity values in Case 2 are primarily due to the toxic substances used in the wind power infrastructure and to a lesser extent, the use of methanol itself in terms of methanol leakage. In Case 1, MGO production is the main driver through the release of toxic gases and substances, but the absolute values are still significantly lower than those in Case 2. Therefore, Case 2 has a higher impact than Case 1.

Ozone Depletion – Case 1 (MGO)
The results for ozone depletion are mainly driven by the production of MGO in both cases. However, in Case 2, MGO is only used as pilot fuel, resulting in significantly lower values compared to Case 1, where MGO is the main fuel.

Particular Matters – Case 1 (MGO)
Similar to the impact categories acidification and climate change, this impact category is primarily affected by the production and combustion of fuels. Therefore, due to Case 1 having a higher emission factor for PM (view Table 7), it results in a higher outcome compared to Case 2.

Photochemical Ozone Formation – Case 1 (MGO)
Photochemical ozone formation is primarily driven by the interaction of sunlight with nitrogen oxides and volatile organic compounds (Pinto et al., 2010). Nitrogen oxides and volatile organic compounds are formed during the combustion of fuels (Louka et al., 2003). In Cases 1 and 2, the photochemical ozone formation is driven by the combustion of MGO and eMeOH,

respectively. These processes have a similar impact, but the slightly higher impact observed in Case 1 is due to the slightly higher impact from the production of MGO.

Resource use, fossil – Case 1 (MGO)

Due to MGO being derived from fossil fuels, it is not surprising that the emissions are higher in Case 1 compared to Case 2. The production of MGO is the main contributor to the emissions in Case 1, while in Case 2, the production of MGO and electricity for methanol production are the main drivers. Similar to ozone depletion, the MGO in Case 2 is only used as pilot fuel, resulting in significantly lower values compared to Case 1, where MGO is the main fuel.

Resource use, minerals and metals – Case 2 (eMeOH)

Case 2 has a higher result for this impact category than Case 1, which can be attributed to the use of critical minerals and metals in the infrastructure for the wind power plant that produces the energy for the methanol production and the methanol production itself. In Case 1, this impact category is primarily driven by the vessel production. However, since both cases are based on the same vessel, this impact is the same for both and is outweighed by the infrastructure impacts in Case 2.

For a direct comparison of Case 1 and Case 2, the normalized results for the twelve impact categories are shown in the following Figure:

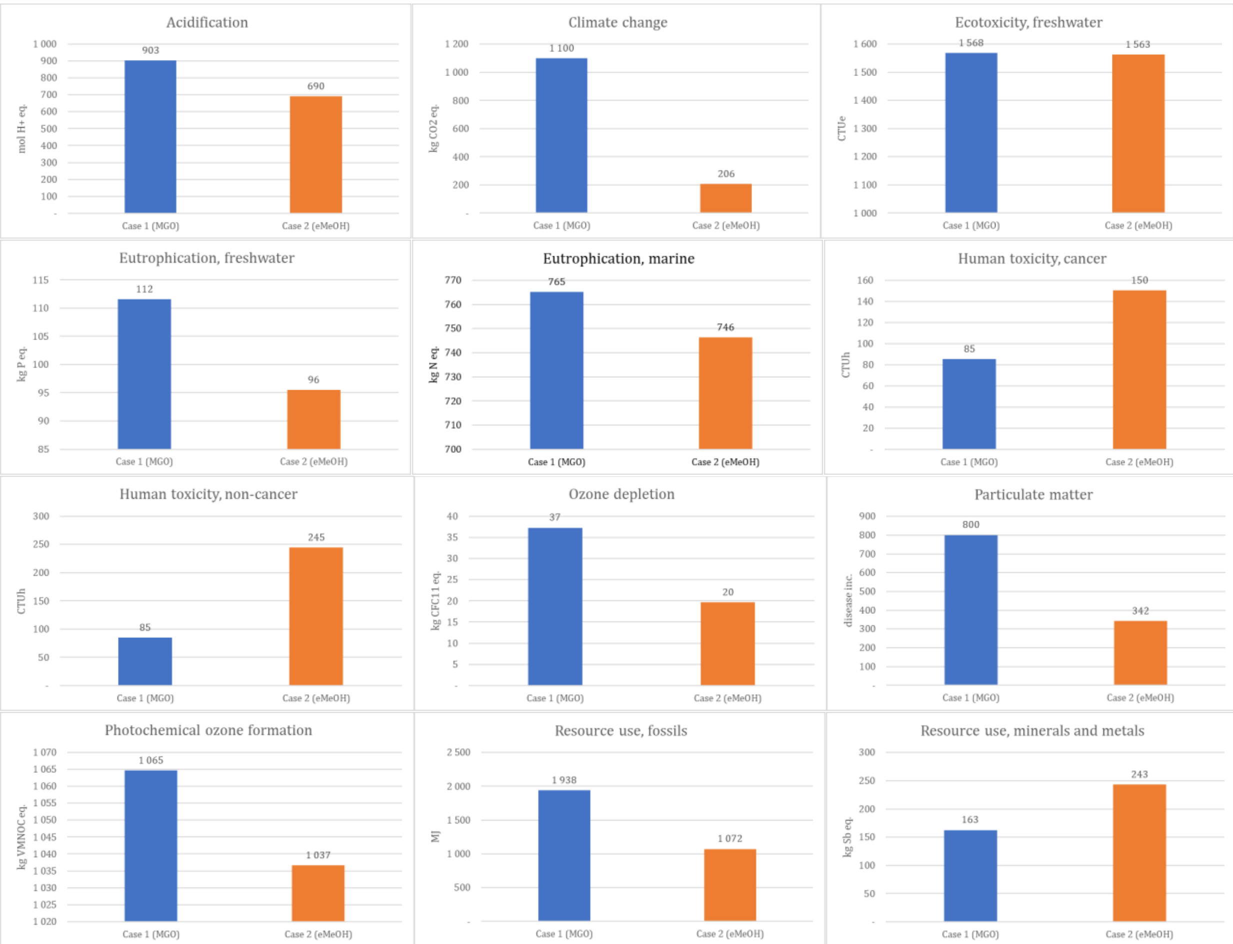


Figure 6: Normalized results based on EF 3.0.

5.1.2 Secondary Functional Unit Results: Ship-specific Parameters

In order to make the results comparable with other ships and ship segments, the additional functional unit "transport of 1 ton of cargo over 1 nautical mile by sea over the life-cycle of the ship" was chosen to represent specific ship parameters and to capture the transport work. The assumed load of the ship is 49%. The characterization results are presented in Table 8. The results obtained are consistent with those of the main functional unit and the explanations for these results are the same as those presented in the previous Chapter 5.1.1. A negative difference indicates that Case 2 has less impact, and a positive difference indicates that Case 1 has less impact.

Table 8: Characterization results and difference in percentage between Case 1 and Case 2 of the functional unit "transport of 1 ton of cargo over 1 nm by sea over the ship's life-cycle".

Impact category	Reference unit	Case 1 – MGO	Case 2 - eMeOH	Difference Case 1 – 2 [%]
Acidification ($x10^3$)	mol H+ eq.	0.44	0.34	24%
Climate change ($x10^3$)	kg CO2 eq.	78.59	14.70	81%
Ecotoxicity, freshwater	CTUe	0.59	0.59	0,4%
Eutrophication, freshwater ($x10^6$)	kg P eq.	1.58	1.35	14%
Eutrophication, marine ($x10^3$)	kg N eq.	0.13	0.13	2%
Human toxicity, cancer ($x10^9$)	CTUh	0.01	0.02	-76%
Human toxicity, non-cancer ($x10^9$)	CTUh	0.17	0.50	-190%
Ozone depletion ($x10^9$)	kg CFC11 eq.	17.65	9.31	47%
Particulate matter ($x10^9$)	disease inc.	4.20	1.80	57%
Photochemical ozone formation ($x10^3$)	kg NMVOC eq.	0.38	0.37	3%
Resource use, fossils	MJ	1.11	0.62	45%
Resource use, minerals and metals ($x10^6$)	kg Sb eq.	0.09	0.14	-49%

The impact category climate change is especially interesting for comparing ships and ship segments with each other and is a relevant indicator in marine policy. Thus, the focus is in the following on the climate change impact category. When comparing the impact measured in grams CO_2eq., Case 1 has 81% more emissions compared to Case 2, with 79 g CO_2eq. and 15 g CO_2eq., respectively. Furthermore, this result demonstrates the potential for reducing emissions by 64 g CO_2 eq. when transitioning from a vessel powered by MGO to one powered by eMeOH with a capacity factor of 49%.

A comparison of the results with the MRV data of general cargo ships in Europe that have reported data (view Figure 7) reveals that Case 1 falls within the higher range and Case 2 within the lower range in terms of climate change impact per transport work. The values for Case 1 and Case 2 are adjusted to include only the effects of the ship operation phase. For Case 1, this is 84% of the total impact, or 65 g CO_2 eq., and for Case 2, 56%, or 8 g CO_2 eq. This indicates that general cargo ships (< 5,000 GT) powered by MGO are a rather inefficient mode of transport for goods in terms of climate change impact, whereby general cargo ships (< 5,000 GT) powered by eMeOH are more efficient compared to the MRV data of general cargo ships that have reported data.

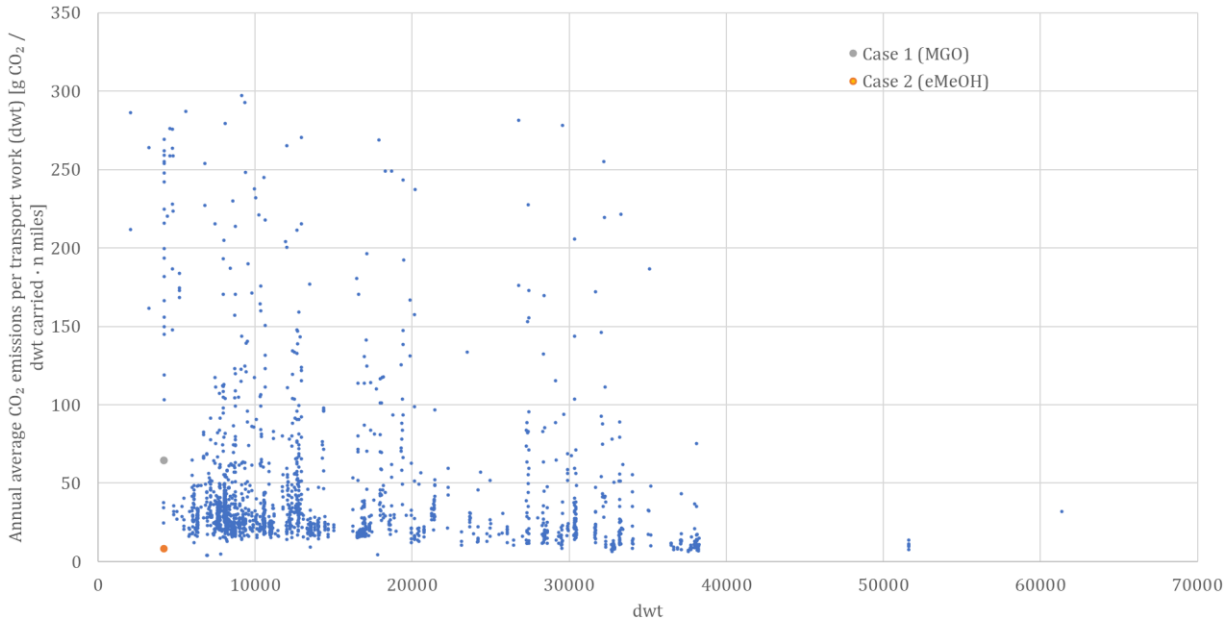


Figure 7: Comparison of annual average CO_2 emissions per transport work for Case 1 and Case 2 and all general cargo ships from MRV data.

5.1.3 Contribution Analysis

Contribution analyses are used to break down results into contributing items. In this study, contribution analyses of the selected impact categories were performed on the characterization results of Case 1 and 2 to identify which groups of processes are hotspots of environmental impacts. The findings can inform industry professionals and other stakeholders of which areas are most worthwhile to improve. The processes were categorized into four groups following the life-cycle phase of the ship: (1) shipbuilding, (2) ship operation, (3) ship maintenance and replacements, and (4) fuel production. The numerical values can be found in Appendix A.11. This contribution analysis is valid for both functional units because it shows the percentage shares of the different life-cycle phases, which are the same for both functional units.

Figure 8 shows that either the ship operation processes or the fuel production processes were the major contributors to most impact categories for Case 1. The ship operation processes were the primary contributors to the impact categories photochemical ozone formation (78%), particular matters (81%), marine eutrophication (87%), climate change (84%), and acidification (67%). Meanwhile, the fuel production processes were the primary contributors to the impact categories resource use (fossil) (96%), ozone depletion (98%), human toxicity (non-cancer) (73%), freshwater eutrophication (51%) and freshwater ecotoxicity (91%). Only the impact categories resource use (mineral and metals) (62%) and human toxicity (cancer) (49%) had the shipbuilding processes as the primary contributors. The ship maintenance and replacement processes made the smallest contributions to all impact categories, ranging only between 0.05% and 2.17%.

In Case 2, the ship operation processes and fuel production processes were major contributors to most impact categories as well, as shown in Figure 9. Ship operation processes were the major contributors to impact categories photochemical ozone formation (79%), particular matters (63%), marine eutrophication (89%), climate change (56%) and acidification (69%). Fuel production processes were the major contributors to impact categories resource use (minerals and metals) (52%), resource use (fossils) (96%), ozone depletion (98%), freshwater eutrophication (54%), human toxicity (cancer) (65%), human toxicity (non-cancer) (93%), and freshwater ecotoxicity (93%). The shipbuilding processes were the major contributor in none of the impact categories. However, they did have a noteworthy impact on freshwater ecotoxicity (37%), human toxicity (cancer) (28%), and resource use (minerals and metals) (42%). The ship maintenance and replacement processes were the least significant contributors to all impact categories, ranging only between 0.09% and 3.44%.

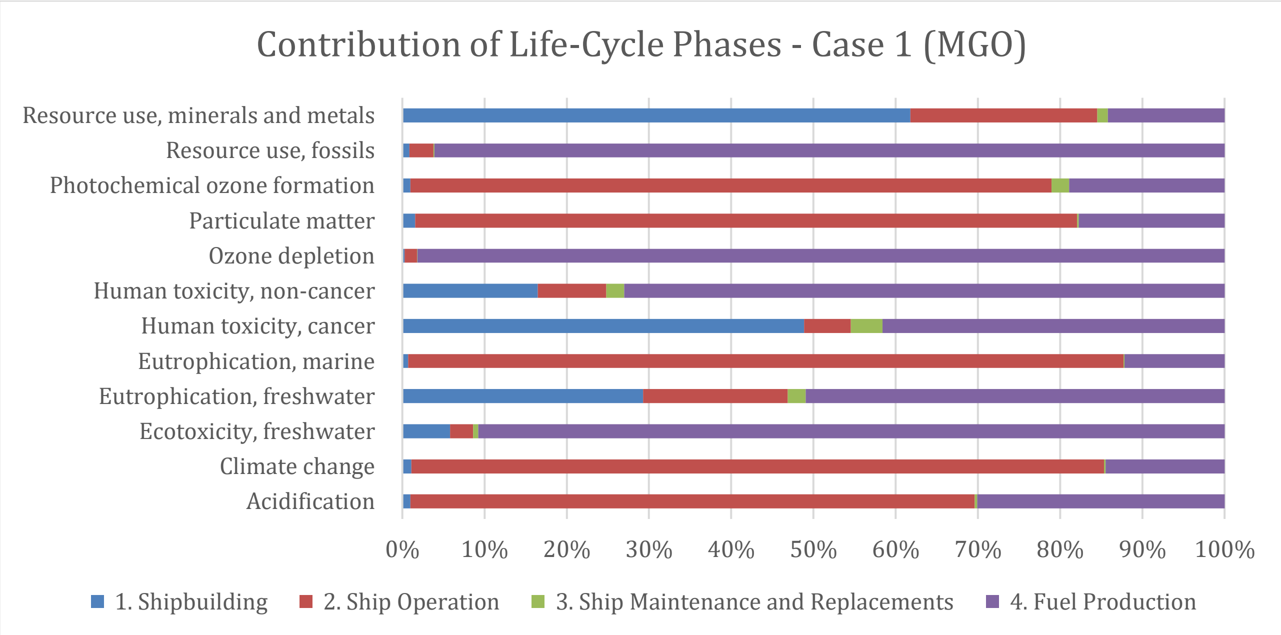


Figure 8: Well-to-wake contribution of process' groups to the life-cycle performance of the "Operation of a general cargo ship (< 5,000 GT) for one year" of Case 1.

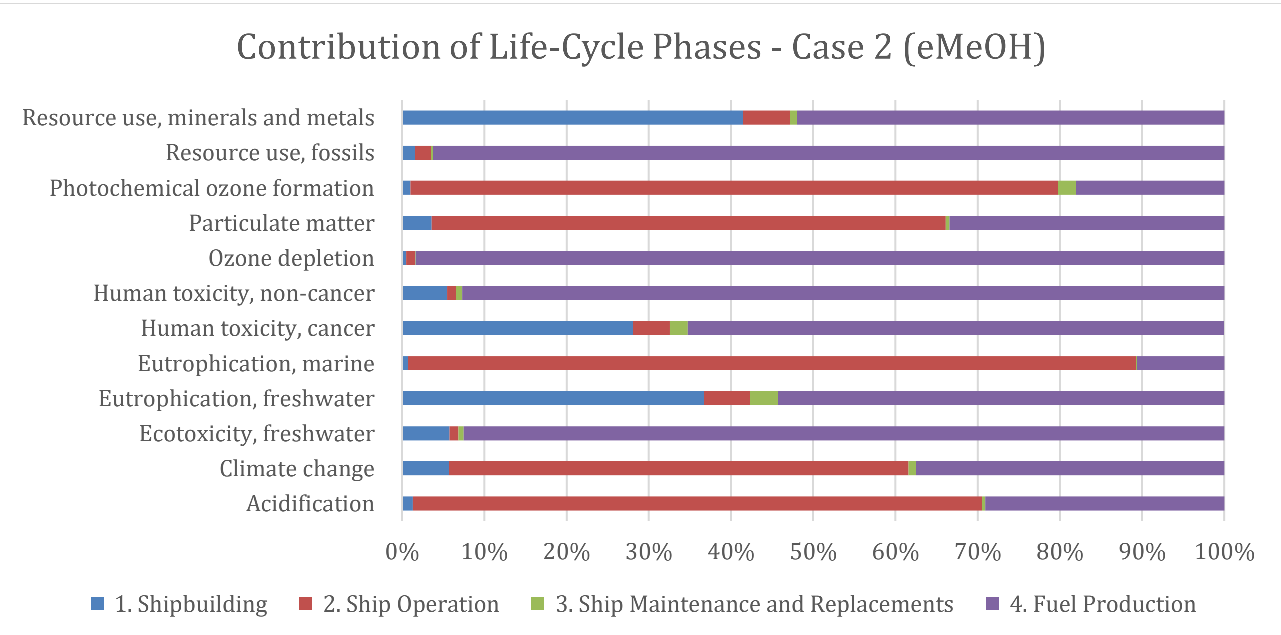


Figure 9: Well-to-wake contribution of process' groups to the life-cycle performance of the "Operation of a general cargo ship (< 5,000 GT) for one year" of Case 2.

When comparing Case 1 and Case 2, it is important to note that for both systems ship operation and fuel production have the most significant impact on the life-cycle performance. The ship maintenance and replacement processes have a negligible contribution to all impact categories for both systems. The main difference between the two systems is that for Case 2, shipbuilding and ship maintenance and replacements were the major contributors to no impact categories. In contrast, for Case 1 shipbuilding was the major contributor for resource use (minerals and metals). For most impact categories in Case 1 and Case 2, the major contributors could be clearly assigned to one of the four phases. However, for the impact categories resource use (minerals and metals), human toxicity (cancer) and freshwater eutrophication in both cases, the shares were more evenly distributed across the four phases. This indicates that for these impact categories, there are several phases of the ship's life-cycle that offer potential for improvement. In summary, the contribution analysis identifies which phase of the ship's life-cycle needs to be improved for each impact category in order to achieve the greatest leverage in improving their life-cycle performance.

5.1.4 Sensitivity Analysis

The reliability and accuracy of a LCA study heavily depends on various input parameters and assumptions, as described in Chapter 3.1.4. Sensitivity analysis investigates how changes in these parameters affect the outcomes (ISO, 2006). Based on the previously described results, the fuel production pathways of the ships were identified as a critical parameter. In addition, there is a high uncertainty regarding the capacity factor. Thus, two sensitivity analyses are conducted for Case 1 and Case 2. The first one addresses the impact of the used fuel production pathways. The second aims to understand the impact of different capacity factors on the life-cycle performance of the ships. Table 9 describes the selected parameters and their ranges.

Table 9: Description of parameters for the sensitivity analysis.

Description of parameter	Parameter ranges
Dataset for the production of MGO	Baseline: Ecoinvent 3.8 (market for diesel, low-sulfur | diesel, low-sulfur | Cutoff, S – Europe without Switzerland) Variation 1 (V1MGO): Ecoinvent 3.8 (market for light fuel oil | light fuel oil | Cutoff, S – Europe without Switzerland)
Electricity used to produce eMeOH	Baseline: Needs (electricity, at offshore wind park 160MW | Scenario: Today) Variation 1 (V1(EU27)): Idemat 2021 (EU-27) Variation 2 (V2(SW)): Idemat 2021 (Sweden)
Capacity factors	Baseline: 49% Variation 1 (V1CF): 30% Variation 2 (V2CF): 68%

5.1.4.1 Fuel Production Pathways

For Case 1, the fuel production pathway and inventory data for MGO is taken from Ecoinvent 3.8 (diesel production, low-sulfur, petroleum refinery operation | diesel, low-sulfur | Cutoff). To assess the sensitivity of this parameter, a different dataset representing the production of MGO. For variation 1 (V1MGO), a different dataset from Ecoinvent 3.8 (light fuel oil production, petroleum refinery operation | light fuel oil | Cutoff, S) was chosen, similar to the study by Malmgren et al. (2021). The results of the sensitivity analysis for the production of MGO for Case 1 are displayed in Table 10.

Table 10: Sensitivity analysis results for Case 1 regarding the twelve impact categories under study using different datasets for the production of MGO.

Impact category	Reference unit	Case 1 (Baseline)	V1MGO	V1 – Case 1 [%]
Acidification ($x10^{-3}$)	mol H+ eq.	50.17	45.25	-10%
Climate change ($x10^{-4}$)	kg CO2 eq.	890.36	810.41	-9%

Ecotoxicity, freshwater (x10^{-4})	CTUe	6,694.11	5,738.28	-14%
Eutrophication, freshwater	kg P eq.	179.26	167.58	-7%
Eutrophication, marine (x10^{-3})	kg N eq.	14.96	13.80	-8%
Human toxicity, cancer (x10^{3})	CTUh	1.44	1.33	-8%
Human toxicity, non-cancer	CTUh	0.02	0.02	-9%
Ozone depletion	kg CFC11 eq.	2.00	1.69	-16%
Particulate matter	disease inc.	0.48	0.43	-11%
Photochemical ozone formation (x10^{-3})	kg NMVOC eq.	43.23	45.86	6%
Resource use, fossils (x10^{-4})	MJ	12,601.29	10,706.64	-15%
Resource use, minerals and metals	kg Sb eq.	10.35	10.38	0.2%

When comparing the baseline results to the results of V1MGO, it is evident that the choice of the dataset used for the production of MGO has a small to medium impact on all impact categories. For most impact categories the characterization results decreased by -7% to -15%. Only for ozone formation and resource use (minerals and metals) the results increased by 6% and 0.2%. This is explained by the differences in the modelling of the refinery processes in the datasets. However, this sensitivity analysis shows that the selection of the variation in this study has a minor impact on the overall results and thus proofs the robustness of the results.

For Case 2, the carbon intensity of methanol varies depending on the feedstock and the production pathway used. As a baseline case, it was assumed that renewable energy from an offshore wind park was used in combination with DAC. However, as revealed in the contribution analysis, the carbon intensity is mainly depended on the electricity used. Therefore, a sensitivity analysis with two different electricity scenarios was conducted. The first scenario assumes that electricity from the European mix is used. The second scenario uses the Swedish mix to reveal how the geographical scope of Sweden may influence the outcomes.

Table 11: Sensitivity analysis results for Case 2 regarding the twelve impact categories under study using different electricity mixes for the production of methanol.

Impact category	**Reference unit**	**Case 2 (Baseline)**	**V1(EU27)**	**V1 – Case 2 [%]**	**V2(SW)**	**V2 – Case 2 [%]**
Acidification (x10^{-3})	mol H+ eq.	38.34	88.73	131%	45.23	18%
Climate change (x10^{-4})	kg CO2 eq.	166.52	1,983.98	1,091%	223.98	35%
Ecotoxicity, freshwater (x10^{-4})	CTUe	6,669.22	5,408.97	-19%	5,408.03	-19%
Eutrophication, freshwater	kg P eq.	153.52	133.78	-13%	133.78	-13%
Eutrophication, marine (x10^{-3})	kg N eq.	14.59	22.18	52%	15.05	3%
Human toxicity, cancer (x10^{3})	CTUh	2.54	1.41	-44%	1.41	-44%
Human toxicity, non-cancer	CTUh	0.06	0.01	-77%	0.01	-77%
Ozone depletion	kg CFC11 eq.	1.06	1.03	-2%	1.03	-2%
Particulate matter	disease inc.	0.20	0.63	208%	0.24	20%
Photochemical ozone formation (x10^{-3})	kg NMVOC eq.	42.09	64.80	54%	43.54	3%

Resource use, fossils (x10-4)	MJ	6,972.91	42,781.05	514%	35,579.95	410%
Resource use, minerals and metals	kg Sb eq.	15.47	10.36	-33%	10.36	-33%

The differences between the baseline results and the variations V1(EU27) and V2(SW), reveal that all outcomes are medium to highly sensitive to the different electricity mixes used during methanol production. Notably, climate change (1091%), resource use (fossils) (514%), particular matters (208%), and acidification (131%) show tremendous increases in the results for V1(EU27). This can be explained by the high share of fossil electricity in the European Mix. In contrast, V2(SW) has a higher share of renewable electricity, resulting in changes that move in the same direction but with a smaller magnitude. For the impact categories freshwater ecotoxicity (-19%), EUF (-13%), human toxicity (cancer) (-44%), human toxicity (non-cancer) (-77), ozone depletion (-2%) and resource use (minerals and metals) (-33%) the same percentual changes for V1(EU27) and V2(SW) were calculated. Moreover, these impact categories are also the ones that improved compared to the baseline scenario. This may be explained by the fact that the determining parameter for the respective changes for this outcome is contained in the baseline scenario dataset and is not contained in the datasets for V1(EU27) and V2(SW). Thus, this demonstrates that renewable electricity from wind power may not always be the optimal choice with a holistic perspective on the life-cycle performance.

In summary, this sensitivity analysis highlights the importance of the used electricity for the production of methanol for all impact categories. When focusing on the climate impact of methanol, the higher the share of renewable electricity the better the outcome for this impact category when looking from the baseline scenario (fully renewable electricity) over V2(SW) (high share of renewables electricity) to V1(EU27) (low share of renewable electricity). In addition, it is important to note that when comparing the climate change impact of V1(EU27) to the climate change results of Case 1, the result of V1(EU27) is more than double. This indicates that the fuel production pathway is essential for determining the life-cycle performance of ships, especially with a focus on the climate change impact.

5.1.4.2 Capacity Factor

The capacity factor is the determining parameter for the transport work of a ship and is embedded in the additional FU. The capacity factor, which represents the percentage of cargo capacity used during transportation, is a crucial factor in determining the climate impact of ships. A higher capacity factor indicates more efficient use of vessel capacity, resulting in reduced CO_2 emissions per unit of cargo transported. Efficient use of cargo capacity reduces the number of voyages needed to transport goods, thereby decreasing fuel consumption and GHG emissions in maritime transportation. Conversely, operating at lower capacity factors results in inefficiencies and increased GHG emissions per unit of cargo transported, as vessels are underutilized. In this study, a baseline capacity factor of 49% was calculated based on the average MRV data. For the sensitivity analysis, capacity factors of 30% for V1CF and 68% for V2CF were

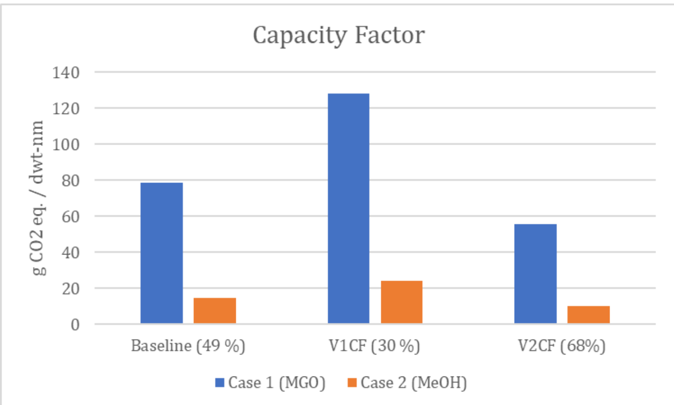


Figure 10: Sensitivity analysis of different capacity factors for the impact category "Climate Change".

selected based on the standard deviation (0.19) of the capacity factor. All characterization, weighted and normalized results of Case 1 and Case 2 can be found in Appendix A.12. Figure 10 shows the results for the different capacity factors for the impact category climate change. This demonstrates that the GHG intensity of the transport work is significantly affected by capacity factors. When considering the average CO_2 emissions per transport work of all ships included in the MRV data (see Figure 7), it becomes apparent that general cargo ships (< 5,000 GT) powered by MGO are even with an optimistic capacity factor of 68% an inefficient mode of transport. In contrast, V1CF and V2CF for Case 1 ranges still in the low impact range comparing to all ships in the MRV data (see Figure 7).

5.1.5 Challenges and Opportunities for General Cargo Ships (< 5,000 GT)

The previous chapters presented the life-cycle performance of two model general cargo ships (< 5,000 GT) powered by MGO and eMeOH. In summary, most impact categories resulted in better life-cycle performance for Case 2 (eMeOH). However, for the impact categories human toxicity (cancer & non-cancer) and resource use (minerals and metals), the methanol-powered ship showed worse outcomes than the MGO-powered ship. When examining the climate change impact of general cargo ships (< 5,000 GT), which is a crucial factor in both national and international policies and regulations, it was found that Case 1 falls within the high-emitting range, while Case 2 falls within the low-emitting range when compared to all general cargo ships included in the MRV data. The contribution analysis revealed that the operational and fuel production phases of the ship have the most significant impact on the life-cycle performance. The sensitivity analysis showed that both systems' fuel production pathways have a medium to high impact on all impact categories. In particular, for Case 2, the carbon intensity of the electricity used to produce methanol is crucial for the ship's climate change impact. Furthermore, it is evident that variations in the capacity factor significantly affect the impact of the transported cargo. Based on these results, this chapter evaluates the main challenges and opportunities for general cargo ships (< 5,000 GT) in terms of improving their life-cycle performance.

For Case 1, the main challenge of the life-cycle performance lies in the impact of producing and combusting MGO. However, this impact is challenging to address because it is caused by the fuel characteristics of MGO as a fossil fuel itself. One possible approach may be switching the fuel to eMeOH as exemplified in this study with Case 2. For Case 2, the main challenge of the life-cycle performance lies as well in the impact of producing and combusting methanol. However, the magnitude of the impact is smaller when directly compared to Case 1. The largest leverage for improving the life-cycle performance of the ships is by using low-carbon methanol. In this study, eMeOH from renewable energy was used representing low-carbon methanol.

Additionally, as both cases are based on the same model ship, the same dataset was used to estimate the life-cycle performance of the vessel, as well as the maintenance and replacement processes. The main difference between Case 1 and Case 2 is that the increased size of the tank was added to the baseline model. The usage of metals, especially steel, is the main driver for the life-cycle impact of all these processes. Improving the life-cycle performance of metals used in the ship, particularly steel, would indirectly enhance their life-cycle performance. For example, the use of recycled metals would be an option. Moreover, as shown in Chapter 5.1.4, a high capacity factor improves the life-cycle performance for all impact categories for Case 1 and Case 2. For example, by increasing the capacity factor from 49% to 68%, the life-cycle performance of all impact categories decreases by 29%. However, it is important to note that this value only provides insights into the weight of the cargo transported and not its volume. Additionally, it does not take into account the life-cycle performance of the entire ship which is captured by the main functional unit of this study. Consequently, in order to reduce the life-cycle impact per transported cargo, it would be beneficial for ships to increase their capacity factor.

After analyzing the LCIA results of Case 1 and Case 2 and discussing their challenges and opportunities, the compliance with the FuelEU maritime regulation concerning emissions and environmental standards for maritime transport is assessed.

5.2 Fuel EU Maritime Regulation

This chapter describes the key aspects of the FuelEU maritime regulation (Regulation (EU) 2023/1805). The FuelEU maritime regulation, which applies to ships of 5,000 GT or more, provides a comprehensive framework for addressing emissions from shipping in the European Union. The regulation covers three different emission scenarios: 100% of emissions on voyages between EU ports, 100% of emissions at berth and 50% of emissions on voyages between an EU port and a non-EU port (referred to as 'semi-full scope' emissions). One of the key provisions of the FuelEU maritime regulation is the implementation of a progressive reduction in the GHG intensity of ships' fuel consumption. This reduction is mandated at 5-year intervals from 2025 to 2050. In addition, the regulation introduces a requirement for certain ships, initially limited to container ships and passenger ships, to connect to shore-side electricity (SSE) or use alternative zero-emission technologies when at berth in ports. This measure aims to reduce emissions during idle periods in ports and thus contribute to overall environmental sustainability.

In addition, the agreement includes a sub-target requiring ships to carry at least 2% Renewable Fuel of Non-Biological Origin (RFNBO) by 2034. This sub-target is subject to the condition that a minimum of 1% RFNBOs has not been achieved by 2031, commonly referred to as the 'sunrise' clause. To facilitate compliance with the GHG intensity targets, a 'multiplier' of 2 will be applied to RFNBOs until the sub-target comes into effect, reducing the required volume of RFNBOs and consequently the associated costs. A notable feature of the regulation is the introduction of a pooling mechanism that allows emissions and RFNBO consumption to be pooled within or between operators, provided they have the same data verifier. This mechanism allows targets to be met on a fleet-wide basis, encouraging cooperation and flexibility in meeting regulatory requirements. In addition, companies are given the flexibility to manage their compliance balance by using a “banking and borrowing” mechanism that allows them to shift compliance between years within certain limits. This provision recognizes the dynamic nature of maritime operations and provides companies with a tool to optimize compliance over time. Furthermore, the regulation is limited to the impact of fuel production and operation, which, as described in the contribution analysis in section 5.1.3, are the most impactful and provide the greatest leverage. The key aspects of the FuelEU Maritime regulation are summarized in Table 12.

Table 12: Summary of the FuelEU maritime regulation. Source: Regulation (EU) 2023/1805

	2020	2025	2030	2035	2040	2045	2050
Required Emission Reduction [%]	Baseline	-2%	-6%	-14.5%	-31%	-62%	-80%
Maximum Emission Intensity [g CO_2eq./MJ]	91.16	89.34	85.69	77.94	62.90	34.64	18.23
RFNBO Multiplier	-	2.0	1.8	1.0	1.0	1.0	1.0
RFNBO Sub-target	-	0.0%	0.4%	2.0%	2.0%	2.0%	2.0%
SSE Mandate	-	-	→	→	→	→	→
Pooling Mechanism	-	→	→	→	→	→	→

5.2.1 General Caro Ships (< 5,000 GT) and the Fuel EU Maritime Regulation

This chapter compares the LCA results of the two case study ships with the goals and requirements of the FuelEU maritime regulation. Since the SSE mandate does not apply to general cargo ships, it is not further evaluated. Based on the WtW emission intensity of the fuels, 90.42 g CO_2eq./MJ for Case 1 and 15.99 g CO_2eq./MJ for Case 2, the differences between the required emission reduction and current emission intensity were calculated (see Table 13). These values are based on the shares of the emissions associated with the fuel production and operational phase (see Chapter 5.1.3). As shown in Table 13, Case 1 would only comply with the requirements of the FuelEU maritime regulation in the timeframe of 2020 to 2024. From 2025 on the emission intensity lies over the goals. In contrast, Case 2 complies from 2020 on to all required emission reduction goals. Electro-methanol from renewable energy, as modelled in this study, is a RFNBO as defined in Directive (EU) 2018/2001. Therefore, the RFNBO multiplier applies. When the RFNBO multiplier is applied, the emission reduction of eMeOH is accounted for by a factor of 2 for the period 2025-2029 and by a factor of 1.8 for the period 2030-2034. This increases the required emission reduction from -82% to -91% for the period 2025-2029 and from -81% to 90% for the period 2030-2034. After 2034, the RFNBO multiplier is 1, thus not relevant for the following years.

Table 13: Comparison of LCA results to required emission reduction from FuelEU maritime regulation.

	2020	2025	2030	2035	2040	2045	2050
Maximum Emission Intensity [g CO_2eq./MJ]	91.16	89.34	85.69	77.94	62.90	34.64	18.23
Required Emission Reduction [%]	*Baseline*	*-2%*	*-6%*	*-14.5%*	*-31%*	*-62%*	*-80%*
Difference required reduction and current emission intensity Case 1 [%]	-1%	1%	6%	16%	44%	161%	396%
Difference required reduction and current emission WITHOUT RFNBO Multiplier intensity Case 2 [%]	-82%	-82%	-81%	-79%	-75%	-54%	-12%
RFNBO Multiplier	-	2.0	1.8	1.0	1.0	1.0	1.0
Difference required reduction and current emission intensity Case 2 WITH RFNBO multiplier [%]	-82%	-91%	-90%	-79%	-75%	-54%	-12%

Note: Emission intensity Case 1 = 90.42 g CO_2eq/MJ; Emission intensity Case 2 = 15.99 g CO2eq/MJ; Green indicates compliance with required emission reduction; Red indicates non-compliance with required emission reduction.

Nevertheless, the previously described potential emission reduction was estimated based on the ship perspective of the model ships used in this study. However, a special feature of the FuelEU maritime regulation is the pooling mechanism that allows emissions and RFNBO consumption to be pooled within or between operators. In 2022, the emission intensity of the general cargo fleet calling Swedish ports was 91.4 g CO_2eq./MJ, having a higher emission intensity than the baseline emission intensity defined in the FuelEU maritime regulation. There is also no difference in the average emission intensity of general cargo ships above or below 5,000 GT. Moreover, this value is slightly higher by 0.98 g CO_2eq./MJ than the emission intensity of Case 1. This may be explained by the differences in carbon intensity of the different fossil fuels used. By applying the pooling mechanism based on the average emission intensity to the general cargo fleet calling Swedish ports in 2022 the following maximum share of fossil fuels, including MGO, MDO, HFO and light fuel oil (LFO), and minimum share of eMeOH were calculated that are necessary to meet the required emission intensity if they were included in the FuelEU maritime regulation. The respective minimum of shares of eMeOH for the different time periods are shown in Figure 11.

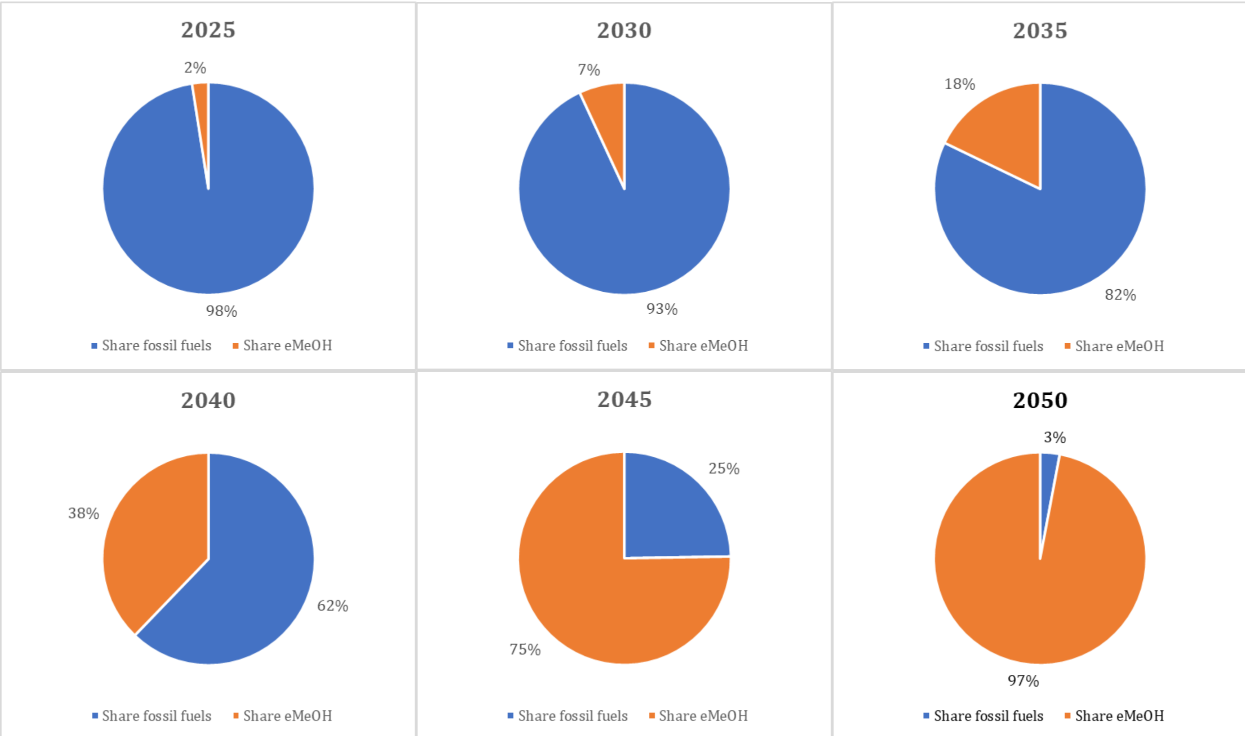


Figure 11: Share of fossil fuels and eMeOH necessary to meet required emission reduction from the FuelEU maritime regulation for the general cargo fleet calling Swedish ports in 2022.

The resulting shares can be applied to a few ships up to the whole fleet because the emission intensity factor is based on the percentual share of the energy content. The share of fossil fuels decreases first slowly from 98% to 82% in a period of 10 years. It is noteworthy that for the period from 2025 to 2034 the RFNBO multiplier applies, reducing the actual required amount of eMeOH to meet the target. From 2040 on the required emission reduction is higher, resulting in an increasing share of eMeOH from 38% to 97%. This simplified model illustrates the magnitude of change, assuming that the emission intensity of the fossil fuels remains the same, required to meet the FuelEU maritime targets using the example of eMeOH. This may help operators in Sweden who want to switch to eMeOH to see the magnitude of change necessary in their fleet. Yet, this model only considers one alternative fuel to fossil fuel, namely eMeOH, with an emission intensity of 15.99 g CO_2eq./MJ, even though in reality there is a wide range of possible low emission fuel and propulsion system options like biofuels, other electrofuels, fuel cells or batteries considered in the FuelEU maritime regulation to reduce the emission intensity of ships. However, evaluating all possible alternative fuel options in one model exceeds the scope of this thesis.

With the RFNBO multiplier, the FuelEU maritime regulation aims to provide ship operators and fuel suppliers with a clear signal of opportunity for investment in the uptake of renewable, scalable, and sustainable fuels (Regulation (EU) 2023/957). This is accomplished by setting an end target for the fuel suppliers (view Table 12), which provides them with certainty regarding future minimum demand. Given that a market for maritime RFNBO has not yet developed, this regulation incorporates flexibility with regard to different possible scenarios for market acceptance of the different low emission fuel and propulsion system options like biofuels, electrofuels, fuel cells or batteries. In Figure 11, the scenario of using eMeOH as RFNBO is shown. However, in this model the impact of the RFNBO multiplier is very small. When comparing the share of fossils fuels and eMeOH with and without applying the RFNBO multiplier the difference is only +1% for the periods 2025 – 2029 and 2030 – 2034 (see Appendix A.13). This means, for example, that for the period 2025-2029, in order to achieve the required emission intensity, the fleet can either run on 2% eMeOH and 98% fossil fuels or on 3% bio-methanol and 97% fossil fuels.

6. Discussion

This section aims to discuss the results in comparison to existing literature, examine the impact of using eMeOH, examine the potential adjustments to the FuelEU maritime regulation, explore the capacity factor and the routes of general cargo ships (< 5,000 GT) and address the limitations of this study.

6.1 Comparison with Literature

When looking at the climate impact of methanol-powered ships, there is a consensus in the literature that there are opportunities for decarbonizing the maritime shipping industry by using electrofuels such as eMeOH (Brynolf et al., 2023; Harahap et al., 2023; Kanchiralla et al., 2022; Kanchiralla et al., 2023). However, the magnitude of this impact is dependent on the energy and carbon source used to produce methanol. Consistent with the findings of this study, eMeOH produced from renewable energy and a non-fossil carbon source has a lower climate impact than MGO (Brynolf et al., 2023; Malmgren et al., 2021; Zincir & Arslanoglu, 2024). Moreover, as shown by the literature review on LCA and LCC for maritime transport by Mondello et al. (2023) most studies focus in terms of impact categories on the climate change impact and in terms of life-cycle phases on the operational phase and production phase of the different marine fuels. As demonstrated by the contribution analysis, these are the most taxing processes for the impact category climate change. However, the focus on the climate change impact and the operational phase of the different marine fuels may neglect possible trade-offs from a ship perspective on other impact categories or overlook improvement possibilities in other life-cycle phases.

Referring to the impact categories other than climate change, a comparison of the results for the eMeOH powered ships in the study by Kanchiralla et al. (2023) with the results in this study, shows that the direction of the results for the different impact categories is consistent. However, given that numerous assumptions and data were derived from Kanchiralla et al. (2023), the comparable outcomes are not unexpected. However, it is noteworthy that the model ships used in Kanchiralla et al. (2023) were RoPax, tanker and service ships and not specifically general cargo ships. Other studies including general cargo ships however mostly focus on the climate change perspective (Brynolf et al., 2023; Zhang et al., 2022), thus the comparison to other impact categories from a general cargo ship perspective is limited. This emphasizes again the knowledge gap regarding the environmental impact of general cargo ships, as previously described in Chapter 1.

One important impact category that is not included in the EF impact assessment method which was used in this study is marine ecotoxicity. According to Carvalho et al. (2024) there is no widely accepted and recommended model for characterizing marine ecotoxicity. Nevertheless, marine ecotoxicity is especially relevant for ships operating in the Baltic Sea and Sweden due to the heavy shipping traffic in this region (Ytreberg et al., 2022). However, the absence of a scientifically recommended characterization model for marine ecotoxicity and its missing in the EF impact assessment method led to the exclusion of this impact category in this study. It is therefore recommended that future life-cycle assessments of small transport ships include marine ecotoxicity, given the increasing threats faced by marine ecosystems (Carvalho et al., 2024).

For the majority of the impact categories, the impact of ship phases maintenance and replacement, as well as ship production, was found to be relatively insignificant. In accordance with this finding, several studies show that the shipbuilding phase only contributes marginally to the overall life-cycle impact (Kanchiralla et al., 2023; Zhang et al., 2022). Still, the majority of LCA studies concentrate on the assessment of a single phase of the ship's life cycle, such as the EoL phase or the operational phase (Mondello et al., 2023).

According to Zhang et al. (2022), cargo ships with larger capacities, measured in dwt, have a higher energy efficiency than ships with lower capacities, whereas small general cargo ships, defined in this context as general cargo ships < 100,000 dwt, show to be the least energy efficient. Similar was shown in Figure 7, whereby here the lower energy efficiency was indicated by a high emission intensity per transport work.

The majority of the studies focus on the climate change impact of ships, with assessments often limited to a single phase of the ship's life-cycle, which is mostly the operational phase. The FuelEU maritime regulation focuses as well only on the climate change impact, whereas this study also considers a number of other environmental impact categories revealing several trade-offs.

6.2 Impact of Usage of electro-Methanol

This chapter discusses the potential impacts and implications of the usage of eMeOH in maritime transport. The LCA results demonstrate that the use of renewable energy in fuel production and the capture of CO_2 from a source that does not drive fossil fuel extraction, such as DAC, can reduce the impact of climate change by utilizing carbon-based electrofuels, such as eMeOH, instead of fossil fuel options, such as MGO. The energy source used in fuel production is influential for the system performance of eMeOH for all impact categories (view Chapter 5.1.4). This is consistent with relevant literature (Brynolf et al., 2023; Kanchiralla et al., 2022; Malmgren, 2023).

Currently, most methanol is produced from fossil sources such as natural gas (IRENA, 2021). By 2050, methanol production is expected to increase fivefold to 500 million tons per year, according to IRENA (2021). Bio-methanol and electro-methanol will account for 80% of this total production. However, this poses challenges to the production infrastructure because producing eMeOH with renewable energy and CO_2 captured from a non-fossil fuel source is necessary for it to have a better climate performance than MGO. Nevertheless, the increased demand for renewable electricity, particularly in Northern Europe and Sweden, aligns with the potential of eMeOH as a sustainable alternative in the maritime sector. Northern Europe, with its abundant wind and hydroelectric resources, presents a favorable environment for the expansion of renewable energy infrastructure for the production of eMeOH (Harahap et al., 2023). Sweden, in particular, stands out for its ambitious renewable energy targets and commitment to decarbonization efforts.

However, the use of methanol has potential trade-offs. The results indicate that methanol can lead to higher human health impacts compared to MGO. Thus, appropriate safety guidelines and regulations need to be introduced for the use of methanol on board ships, as well as during the production of methanol. As methanol is toxic to humans and the environment, crews must be trained to deal with methanol as a fuel. In addition, measures must be taken to prevent and contain fires, as methanol is a low flash point fuel. These characteristics require special safety measures to prevent the formation of methanol vapors and the installation of appropriate ventilation, leak detection, heat detection, and fire suppression equipment (Methanol Institute, 2023). This may result in an increase in the cost of methanol usage.

In addition, the use of methanol showed to have a higher impact for the resource use (minerals and metals). This result is driven by the use of critical minerals and metals in the infrastructure for the wind power plant and methanol production. For example, wind power requires more material per energy output compared to other forms of electricity generation (Schreiber et al., 2019). The environmental impact of materials used for wind power may be reduced in the future if the materials are recycled or reused. Apart from minerals and metals used in windmill components, resource use is significant for the electrolyzer, as well. Nevertheless, future technological advancement may potentially mitigate these negative impacts.

Compared to climate change impacts, there is higher uncertainty for resource use (minerals and metals) and human toxicity (cancer & non-cancer) within the EF v3.0 method. Climate change assessments benefit from robust models, consistent data, and well-established metrics, leading to relatively low uncertainty (Henriksson et al., 2015; Laurent et al., 2012). In contrast, a substantial portion of available toxicity data, under which human toxicity (cancer & non-cancer) falls, is often excluded due to incomplete or imprecise information (Saouter et al., 2019) and varies significantly based on regional and temporal factors (Crenna et al., 2019), leading to high uncertainty in the results. For resource use (minerals and metals) the complexity of global supply chains (Nansai et al., 2015), lack of comprehensive data (Castellani et al., 2019), and regional variability in environmental impacts (Verones et al., 2017) introduce significant uncertainty. This means that that the results for these impact categories must be treated with more caution than the climate change impact and the magnitude of these trade-offs may vary.

From a policy perspective, it is still necessary to consider the trade-offs of using eMeOH. If policy makers aim to support the uptake of eMeOH as a maritime fuel, as has been done in the FuelEU maritime regulation, it is essential to consider the trade-off with especially human toxicity (cancer & non-cancer) and resource use (minerals and metals), taking into account their uncertainties, as well as safety aspects and infrastructure constraints. The FuelEU maritime regulation currently does not consider any of these trade-offs. Only with regard to the production infrastructure, the RFNBO multiplier and the RFNBO subtarget are designed to enhance the competitiveness of eMeOH. However, the environmental impacts of eMeOH, which extend beyond climate change, such as human toxicity (cancer & non-cancer) and resource use (minerals and metals), are not addressed. In particular, the trade-off with resource use (minerals and metals) will be critical in the future, as increasing social and environmental pressure is expected to be placed on the extraction of metals required for the renewable energy systems needed to produce sustainable eMeOH (Lèbre et al., 2020). Nevertheless, methanol, particularly eMeOH, presents a low-carbon solution in the short term due to its adaptability with the existing fossil fuel bunkering infrastructure and its retrofitability with existing ICE (Wang et al., 2024), making it an important element of the FuelEU maritime regulation.

6.3 FuelEU Maritime Regulation: The RNFBO multiplier and Default WtW Emission Factors for eMeOH

The RFNBO multiplier is a crucial element of the FuelEU maritime regulation and aims to stimulate the adoption of alternative fuels. However, a comparison of the share of fossil fuels and eMeOH with and without the application of the RFNBO multiplier reveals a difference of only +1% for the periods 2025–2029 and 2030–2034 (see Appendix A.13). This prompts the question of the effectiveness of the RFNBO multiplier and whether the 1% difference between using RFNBO and non-RFNBO fuels will truly promote the uptake of these fuels. This finding is supported by Transport & Environment (2021) which even suggest to increase the multiplier to 5 in order to enhance the competitiveness of electrofuels like eMeOH. Furthermore, the lower the emission intensity of the alternative, the less of it is necessary to achieve the required emission intensity.

In addition to the RFNBO multiplier as a policy incentive, several other factors need to be considered to effectively promote the adoption of alternative fuels in maritime transportation. These factors include for instance higher fuel cost for alternative fuels (Law et al., 2021; Schwartz et al., 2022), infrastructure availability (Prussi et al., 2021), GHG savings (Prussi et al., 2021; Xing et al., 2021) technical maturity and safety (Deniz & Zincir, 2016; Prussi et al., 2021) and other policy incentives such as subsidies, tax incentives, and stringent emission regulations (Chu Van et al., 2019). These additional considerations highlight the complexity of promoting alternative fuels like eMeOH and suggest that a multifaceted approach, including but not limited to the RFNBO multiplier, is necessary to achieve significant progress in the maritime sector.

The fleet emission intensity in Chapter 5.2.1 was estimated using the default values from the FuelEU maritime regulation, as the regulation requires the use of default well-to-tank (WtT) emission values for fossil fuels (Regulation (EU) 2023/1805). Moreover, when looking at the default values for eMeOH in the FuelEU maritime regulation, only values from TtW for CO_2 are provided that are 1.375 g CO_2 per g fuel. For RFNBO fuels like eMeOH, it is not required to use default WtT emission values like for fossil fuels. Their WtW emission intensity shall be calculated using the methodology in Article 28(5) of the Directive (EU) 2018/2001. This is logical given the significant discrepancies in emission intensity based on the production pathway and electricity source for eMeOH as shown in the sensitivity analysis. However, in the early stages of adopting eMeOH, it may be beneficial to provide WtT emission factors for eMeOH. This will enhance the planning security for ship operators, as they will be able to calculate the minimum required share of eMeOH necessary to meet the required emission intensity.

6.4 FuelEU Maritime Regulation: Risks and missed Opportunities by excluding General Cargo Ships (< 5,000 GT)

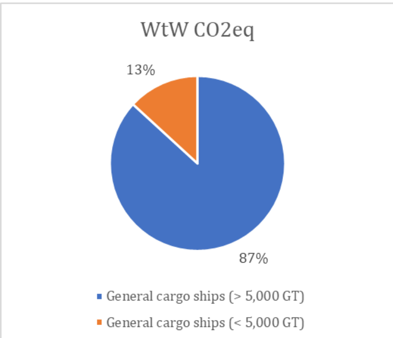


Figure 12: Share of total WtW $MtCO_2eq$. of the general cargo fleet calling Swedish ports in 2022. Source: Styhre et al. (2024) & own calculations

The Fuel EU maritime regulation only applies to ships larger than 5,000 GT. As shown in Figure 12, the share of total WtW CO_2eq. emission of general cargo ships (< 5,000 GG) calling Swedish ports in 2022 was 13%. In absolute numbers, derived from Styhre et al. (2024) and adjusted by own calculations, general cargo ships (> 5,000 GT) emitted 0.87 Mt CO_2eq. and general cargo ships (< 5,000 GT) emitted 0.13 Mt CO_2eq. Comparing to the total domestic and international transport emissions in Sweden in 2022 which were 22.5 Mt CO_2eq., the share of general cargo ships (< 5,000 GT) accounted for 4% (Swedish Environmental Protection Agency, 2023a, 2023b). This shows that there is a non-negligible share of emissions for general cargo ships (< 5,000 GG) even though they are not included in the Fuel EU maritime. Moreover, general cargo ships (< 5,000 GT) make up to 73% of the total general cargo fleet calling Swedish ports in 2022 (Styhre et al., 2024), meaning that the smaller general cargo fleet makes the majority of the port calls in Sweden. Even though that the majority of the ships makes the smaller share of emissions (see Figure 12), there are several risks and missed opportunities by not including ship below 5,000 GT. Thus, next the risks and missed opportunities of excluding (general cargo) ships below 5,000 GT from the FuelEU maritime regulation are discussed.

A study by Transport & Environment (2022) investigating the emissions from vessels under 5,000 GT from 2019 and in segments not covered by the MRV regulation, found that ships under 5,000 GT make up a total of 19.7 $MtCO_2$. In addition, ships just the 5,000 GT threshold are shown to have higher average emissions than ships above the threshold (Transport & Environment, 2022). However, it is noteworthy that in the study of Transport & Environment (2022) general cargo ships were not classified in any category, therefore it is unclear how and to what extent they were included in this study. Nevertheless, as described in the previous Chapter 5.2.1, the climate impact of general cargo ships (< 5,000 GT) calling Swedish ports in 2022 is not negligible. This shows that ships below 5,000 GT have a non-negligible climate impact and the exclusion of these ships in the Fuel EU Maritime regulations and other European legislation is questionable. Transport & Environment (2022) suggests that policymakers should reduce the threshold to 400 GT. An effective threshold was not evaluated in this study. Nevertheless, a threshold of 400 GT may serve as a suitable reference for initiating a discussion on the optimal threshold that can be evaluated in future studies.

In December 2023, the first vessel of a series of 5,350 dwt plug-in hybrids, Electramar, was delivered (AtoB@C, 2024). At 4,135 GT, the Electramar is a recent example of innovation in green shipping for general cargo ships under 5,000 GT. However, ships under 5,000 GT will not be subject to uniform European decarbonization legislation, while ships over 5,000 GT will be required to pay for their greenhouse gas emissions under the EU's ETS and are forced to gradually switch to cleaner fuels under the FuelEU Maritime Regulation. As a result, there is no incentive for these ships to switch to greener and often more expensive fuels (Law et al., 2021; Schwartz et al., 2022). Therefore, it will be very difficult for ship operators to build green business cases to compete with ships using conventional fossil fuels. The European Commission is missing a great opportunity to stimulate maritime innovation by exempting ships under 5,000 GT. As shown by the example of AtoB@C with plug-in hybrids, but also for other alternative propulsion systems like methanol, battery or fuel cells, alternative technologies, will first be used in smaller vessels before being scaled up for use in larger vessels (Transport & Environment, 2022). As such, the decision to exempt all (general cargo) ships below 5,000 GT from the FuelEU maritime regulation and most European legislation is questionable and may further delay decarbonization in a sector that needs regulatory guidance to reduce its climate impact.

6.5 Increase of Capacity Factor and Change of Propulsion System and Fuel

There is often the discussion if an increase of capacity factor or a change of fuel or propulsion system is more effective in term of improving the environmental impact of ships. As already briefly described in 5.1.5, a high capacity factor improves the life-cycle performance for all impact categories for Case 1 and Case 2. For example, by increasing the capacity factor from 49% to 68%, the life-cycle performance of all impact categories decreases by 29%. Vice versa by decreasing the capacity factor from 49% to 30%, the life-cycle performance of all impact categories increases by 63%. This illustrates the disproportionate relationship between a high or low capacity factor, which results in a low or high impact. In contrast, a change of fuel as exemplified in the LCA analysis of Case 1 and Case 2, does not result in a clear direction and magnitude of change for all impact categories. As shown in Figure 5, changing from a MGO powered ship to an eMeOH powered ship leads to improvement in most impact categories except of human toxicity (cancer & non-cancer) and resource use (minerals and metals) whereby the percentual change of improvement ranges from 0.4% to more than 81%. This demonstrates that enhancing the capacity factor is a more straightforward approach to improving the life-cycle performance than switching the fuel or propulsion system, which is a more complex consideration that can be more effective.

Moreover, ship operators typically aim to maximize the capacity factor of their ships as this leads to lower operating costs per unit of cargo transported, as fixed costs are spread across more goods. Thus, the room for improving the capacity factor may be limited. Nevertheless, the average capacity factor for general cargo ships reporting correct data to the MRV database was found to be 49% (view Chapter 4.2.2.1), less than half, indicating that there is still room for improvement in this area. However, the capacity factor is a metric that only correlates to the impact of the transported cargo, rather than the ship itself. For example, ship operators only focusing on enhancing the capacity factor may overlook potential impact reduction measures like switching the fuel or propulsion system of the ship that may be higher in absolute numbers. Alternative fuels are currently more expensive or less economically viable compared to traditional fossil fuels. Nevertheless, policies such as the FuelEU maritime regulation are attempting to enhance the competitiveness of alternative fuels, including eMeOH, to foster a switch of fuel and propulsion systems. However, this requires large investments from ship operators. Consequently, enhancing the capacity factor may be perceived as a more straightforward approach than switching the fuel. While the improvement achieved through fuel switching is more enduring and less fluctuating than that of capacity factor, which can vary from trip to trip.

In summary, increasing the capacity factor of ships has a more consistent impact on their environmental footprint than changing fuel or propulsion systems. However, while enhancing the capacity factor is often a more straightforward option for ship operators, it has limitations. Switching to alternative fuels, though more complex and costly, can provide more sustainable long-term benefits.

6.6 Routes of General Cargo Ships (< 5,000 GT)

In addition to the capacity factor or fuel switch, the routes of ships play a key role in maritime transport in terms of determining alternative propulsion systems. This chapter discusses the frequency of distances of general cargo ships (< 5,000 GT) based on Swedish port call data from 2022 and the resulting implications for general cargo ships (< 5,000 GT). Figure 13 presents a pareto histogram of the frequency of distances for general cargo ships (< 5,000 GT) in descending order of frequency. A Pareto histogram combines a bar chart displaying the frequencies of different unique routes categorized per 100 nm with a line chart representing the cumulative percentage of those categories. It visually highlights the most significant routes by showing which categories of distances contribute the most to the cumulative total. This indicates that 80% of the distances are routes with a distance of less than 600 nm. Furthermore, the most frequent distances, namely routes between 0 to 250 nm, account for around 50% of all routes. The frequency significantly drops after the 300 to 400 nm category. This demonstrates that general cargo ships (< 5,000 GT) are predominantly operating short distances and rarely travel more than 600 nm. In summary, the figure shows that the majority of port distances are short, concentrated within the lower 100 nm categories, and only a small proportion of distances are longer, exceeding 1,200 nm.

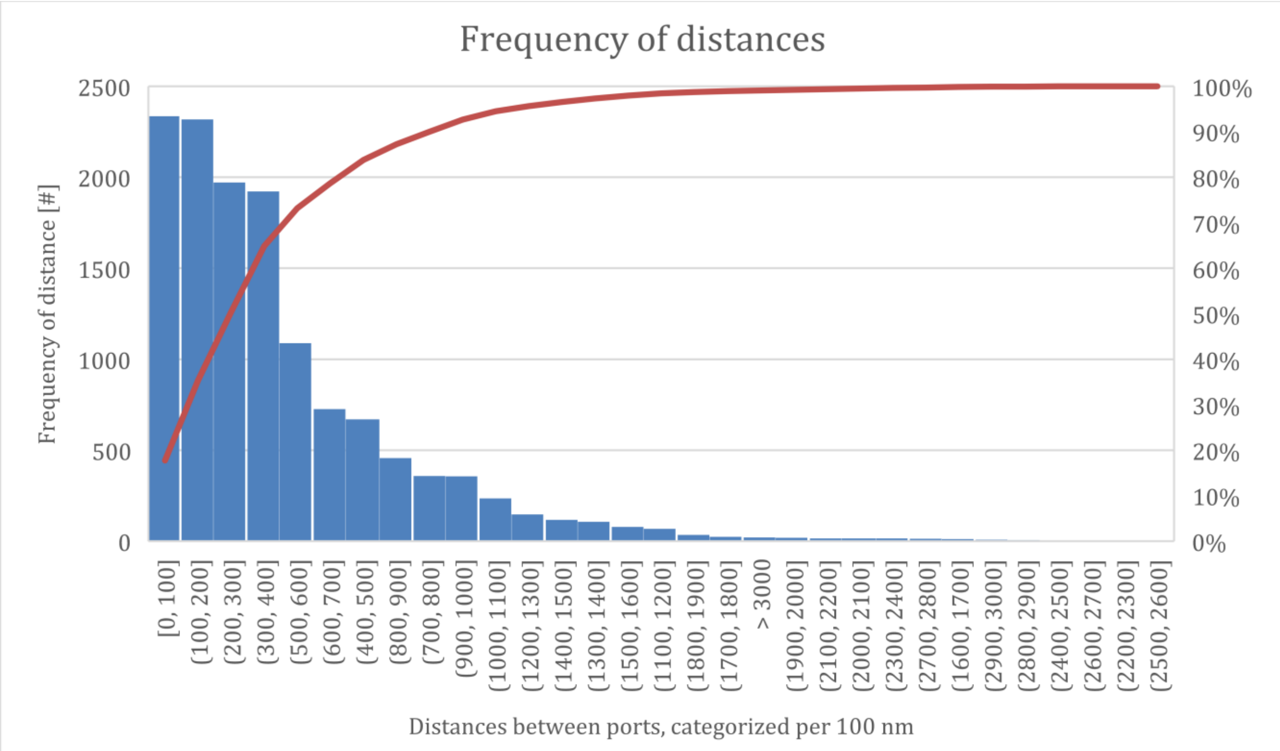


Figure 13: Pareto histogram showing the frequency of distances for general cargo ships (< 5,000 GT) in descending order of frequency. Source: Styhre et al. (2024) & own calculations

The battery powered ship (Case 3) was excluded as reasoned in Chapter 4.1. However, the exclusion was mainly based on the assumption that the battery is sized for a maximum distance of 1,000 nm with a reserve capacity of 60%. The maximum distance of 1,000 nm was chosen based on the maximum distance of the model ship and to include 90% of the possible routes. However, as illustrated in Figure 13, nearly 50% of the routes are shorter than 250 nm. The economic feasibility of battery systems with reduced battery size is rapidly improving, making them viable for short-sea shipping. According to Kersey et al. (2021) future battery costs of $100 per kWh would make electrifying routes under 1,000 km economically viable, with only a slight effect on the ship's carrying capacity. Projected declines in battery prices could potentially increase this feasible range even further(Kersey et al., 2021). In addition, the adoption of battery electric propulsion for general cargo ships traveling shorter routes could yield significant environmental benefits. Battery electric propulsion offers several environmental benefits compared to fossil fuel powered vessels. These include lower GHG emissions, lower acidification, ozone creation and eutrophication potential (Jeong et al., 2020; Perčić et al., 2020; Perčić et al., 2024). Consequently, full electrification may be a viable and reasonable option for general cargo ships (< 5,000 GT), particularly when travelling shorter routes.

Based on Figure 13, there are also potential implications for methanol powered general cargo ships (< 5,000 GT). Given that the energy density of methanol is 2.4 times lower than that of MGO, it was assumed that the fuel tanks on a methanol-fueled ship would be 2.4 times larger than those on a ship using MGO. However, since the routes for general cargo ships (< 5,000 GT) are relatively short, a lower factor than 2.4 may be reasonable. This would result in a potential lower material consumption for the tanks and weight and volume gains. These factors may lead to a potentially improved economic utilization of the ship as well as potentially make retrofitting of ships from MGO to methanol more attractive.

6.7 Assessing the Technical Viability

The method for assessing the technical viability as described in Chapter 4.1 may be too simplistic as indicated in the previous Chapter 6.6. The model uses mass and volume ratios (PMM/dwt and PMV/GT) as the primary criteria for assessing feasibility. While these are important factors, they do not account for other critical aspects such as operational range, technological maturity, environmental impact, regulatory compliance or economic factors. By focusing primarily on mass and volume constraints, the model may miss out on these broader factors which could be crucial for a comprehensive feasibility assessment. A more holistic approach that incorporates these additional dimensions would provide a more realistic evaluation of the technical viability of different propulsion systems. However, due to the limited timeframe, the used method was still considered sufficient for the purpose of this study.

6.8 Limitations

The LCA model is limited by the lack of available and high-quality data on technical performance, emission profiles and material demand for the assessed model ships. The secondary data for these parameters were derived from S&P Global (2024a), Styhre et al. (2024) and the MRV data, thus limited by their accuracy and correctness. The material composition of the ships is based on the average material composition of different general cargo ships by Jain et al. (2016) and thus, very generic. Regarding the infrastructure necessary to refuel the ships, especially the eMeOH ships, the assumption was made that it is sufficiently developed. However, this is a very optimistic assumption, especially for the selected production pathway of eMeOH. Methanol bunkering is comparable to MGO or HFO bunkering in that methanol remains liquid at ambient temperature and pressure. Consequently, the same infrastructure that is used to store and bunker traditional marine fuels can be used for methanol, with only minor and inexpensive modifications (Methanol Institute, 2023). Thus, the assumption that the bunkering infrastructure is sufficient was considered appropriate because the existent fossil fuel infrastructure could be employed. Regarding the production infrastructure, according to IRENA (2021) most methanol is still produced from fossil sources in 2020. Nevertheless, for the purpose of comparing the usage of MGO and sustainable eMeOH in general cargo ships, this assumption was considered acceptable because the share of electro-methanol is expected to account for 80% of total production in 2050 (IRENA, 2021). This means that in the coming years, the eMeOH production is expected to increase whereby especially Sweden offers great opportunities to produce sustainable eMeOH with its large renewable energy potential (Harahap et al., 2023). This aligns with initiatives of companies like "Liquid Wind", which are focusing on producing sustainable eMeOH (Liquid Wind, 2024). Thus, the used production pathway for eMeOH is considered realistic. Nevertheless, the results for Case 2 are limited by the assumption of using sustainable eMeOH from renewable energy and DAC which only represent a very small share of the total methanol production in 2022.

The dataset for the maintenance of the ships was derived from Ecoinvent 3.8 from the process of the maintenance of a bulk carrier for dry goods. No specific literature was found on the maintenance of general cargo ships as well as if there are significant differences in the maintenance of an MGO-powered or eMeOH-powered ship, therefore the dataset from Ecoinvent was taken. The maintenance and replacements processes only impacted all impact categories by less than 4% for both cases (see Chapter 5.1.3). Therefore, the selected dataset was considered acceptable. However, since the dataset is not specifically for general cargo ships, but for bulk carriers, the implications derived from the maintenance phase are limited. Moreover, the secondary FU of "*transport of 1 ton of cargo over 1 nm by sea over the ship's life-cycle*" incorporates ship specific parameters like the dwt and the capacity factor. Nevertheless, general cargo ships, which represent a broad category, transport a variety of goods that cannot always be quantified by weight (Korberg et al., 2021), as is the case with the used secondary FU. Therefore, implications on the cargo in terms of volume are limited. It is important to be aware that this functional unit is based on weight and not volume. Furthermore, parameters like the cost of the different alternatives, safety considerations, acceptance or energy security were not assessed due to the limited timeframe of the study. However, these parameters may influence the choice of adopting alternative fuels like eMeOH and thus, limit the conclusiveness of this study.

From a policy perspective, the results of this study are limited by focusing on only one RFNBO fuel, namely eMeOH. Due to the limited temporal scope of this thesis, it was not possible to conduct further research on other fuels. Nevertheless, this was considered an appropriate methodology for demonstrating the intended magnitude of change as well as the effectiveness of the RFNBO multiplier, as outlined in the FuelEU maritime regulation. However, it is acknowledged that the absolute numbers may be biased, yet the direction and magnitude of change can be illustrated and potential improvement possibilities revealed.

7. Conclusion

By performing a life-cycle assessment of two general cargo ships (< 5,000 GT) powered by MGO (Case 1) and eMeOH (Case 2), this research aimed to assess the life-cycle performance of general cargo ships (< 5,000 GT) representing small transport ships. In addition, their potential compliance with the FuelEU maritime regulation was assessed.

Overall, the results demonstrated that Case 2 exhibits a generally favorable life-cycle performance than Case 1. For the impact categories human toxicity (cancer & non-cancer) and resource use (minerals and metals) Case 2 showed worse outcomes than Case 1. Case 1 has 81% more emissions compared to Case 2, with 79 g CO_2eq. and 15 g CO_2eq. per 1 ton of cargo over 1 nm by sea over the ship's life-cycle. The sensitivity analysis showed that both systems' fuel production pathways have a medium to high impact on all impact categories. The contribution analysis revealed that the operational and fuel production phases of the ship have the most significant impact on the life-cycle performance for both cases. Even though the maintenance and replacement processes were no major contributors to the life-cycle performance of Case 1 and Case 2, the inventory analysis revealed a lack of current and specific data for general cargo ships (< 5,000 GT). Moreover, specific data relating to the operation, material composition and maintenance and replacement processes was not available for general cargo ships (< 5,000 GT). Consequently, the conclusiveness for general cargo ships (< 5,000 GT) is limited due to the necessity of utilizing a significant amount of secondary data from other ship types.

For Case 1 the main challenge is the high environmental impact from producing and combusting MGO. This impact is difficult to mitigate due to the inherent properties of MGO. Opportunities for improvement include transitioning to alternative fuels, such as eMeOH. For Case 2 the challenges include higher impacts in human toxicity and resource use (minerals and metals) due to the production processes of methanol. However, opportunities exist in reducing overall environmental impacts, particularly in climate change, by utilizing low-carbon methanol produced from renewable energy sources and DAC. Additionally, improving the capacity factor and the life-cycle performance of metals used in the ship construction presents further opportunities for enhancement.

The two case studies demonstrated varying levels of compliance with the emission reduction requirements of the FuelEU maritime regulation, whereby Case 1 only complies in the first period from 2025-2029. Case 2 shows consistent compliance with the targets, particularly when considering the RFNBO multiplier. Comparing to the Swedish general cargo fleet the share of eMeOH needs to rise from 2% to 97% until 2050 to comply with the required emission intensities. The efficacy of the RFNBO multiplier in stimulating the adoption of low-emission fuels, such as eMeOH, requires further investigation. The exclusion of ships below 5,000 GT from the FuelEU maritime regulation presents a risk of missing emission reduction opportunities. Including smaller vessels in this regulation may provide an incentive for the adoption of greener technologies.

Future work can be built on this study and further investigate the life-cycle impact of small transport ships by including marine ecotoxicity or more detailed real-world operational data. Furthermore, other aspects, such as safety and the infrastructure requirements for the widespread use of eMeOH may be further investigated. From a policy perspective, future research could deepen the understanding of the broader implications of excluding smaller vessels from the FuelEU maritime regulation. This may include exploring the economic and environmental consequences of such exclusions, as well as identifying strategies to incentivize emission reductions in these overlooked segments of the maritime industry. Moreover, continued efforts are required to enhance the availability and accuracy of data for small transport ships, particularly with regard to operational parameters such as fuel consumption and efficiency, material composition and maintenance and replacement processes. By continuing to investigate these areas, policymakers and ship operators can make informed decisions that will drive meaningful progress towards more sustainable maritime transport.

References

Ait Allal, A., Mansouri, K., Youssfi, M., & Qbadou, M. (2019). Toward an evaluation of marine fuels for a clean and efficient autonomous ship propulsion energy. *Materials Today: Proceedings*, *13*, 486–495. https://doi.org/10.1016/j.matpr.2019.04.005

AtoB@C. (2024). *Frontpage | AtoB@C Shipping*. https://www.atobatc.se/

Bicer, Y., & Dincer, I. (2018). Environmental impact categories of hydrogen and ammonia driven transoceanic maritime vehicles: A comparative evaluation. *International Journal of Hydrogen Energy*, *43*(9), 4583–4596. https://doi.org/10.1016/j.ijhydene.2017.07.110

Brynolf, S., Hansson, J., Kanchiralla, F. M., Malmgren, E., Fridell, E., Stripple, H., & Nojpanya, P. (2023). *Life Cycle Assessment of Marine Fuels in the Nordic Region – Task 1C: Roadmap for the introdcution of sustainable zero carbon fuels in the nordic region.* Nordic Roadmap Publication No.1-C/1/2023.

Brynolf, S., Magnusson, M., Fridell, E., & Andersson, K. (2014). Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels. *Transportation Research Part D: Transport and Environment*, *28*, 6–18. https://doi.org/10.1016/j.trd.2013.12.001

Carvalho, B. C., Souza Junior, H. R. A. de, & Soares, S. R. (2024). Evaluation of LCIA characterization models for marine ecotoxicity. *The International Journal of Life Cycle Assessment*, *29*(4), 706–732. https://doi.org/10.1007/s11367-023-02277-4

Castellani, V., Beylot, A., & Sala, S. (2019). Environmental impacts of household consumption in Europe: Comparing process-based LCA and environmentally extended input-output analysis. *Journal of Cleaner Production*, *240*, 117966. https://doi.org/10.1016/J.JCLEPRO.2019.117966

Chu Van, T., Ramirez, J., Rainey, T., Ristovski, Z., & Brown, R. J. (2019). Global impacts of recent IMO regulations on marine fuel oil refining processes and ship emissions. *Transportation Research Part D: Transport and Environment*, *70*, 123–134. https://doi.org/10.1016/J.TRD.2019.04.001

Crenna, E., Secchi, M., Benini, L., & Sala, S. (2019). Global environmental impacts: Data sources and methodological choices for calculating normalization factors for LCA. *The International Journal of Life Cycle Assessment*, *24*(10), 1851–1877. https://doi.org/10.1007/s11367-019-01604-y

Delpierre, M., Quist, J., Mertens, J., Prieur-Vernat, A., & Cucurachi, S. (2021). Assessing the environmental impacts of wind-based hydrogen production in the Netherlands using ex-ante LCA and scenarios analysis. *Journal of Cleaner Production*, *299*, 126866. https://doi.org/10.1016/j.jclepro.2021.126866

Deniz, C., & Zincir, B. (2016). Environmental and economical assessment of alternative marine fuels. *Journal of Cleaner Production*, *113*, 438–449. https://doi.org/10.1016/J.JCLEPRO.2015.11.089

Deutz, S., & Bardow, A. (2021). Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. *Nature Energy*, *6*(2), 203–213. https://doi.org/10.1038/s41560-020-00771-9

Directive (EU) 2018/2001. Directive (EU) 2018/2001 of the European Parliament and of the Council - of 11 December 2018 - on the promotion of the use of energy from renewable sources. *Official Journal of the European Union*. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001

Dong, D. T., & Cai, W. (2019). A comparative study of life cycle assessment of a Panamax bulk carrier in consideration of lightship weight. *Ocean Engineering*, *172*, 583–598. https://doi.org/10.1016/j.oceaneng.2018.12.015

Ecoinvent 3.8. (2021). *ecoinvent, Allocation, cut-off by classification, ecoinvent database version 3.8*. https://ecoinvent.org/

EMSA. (2023). *The EU Maritime Profile – the maritime cluster in the EU*. https://emsa.europa.eu/eumaritimeprofile/section-2-the-eu-maritime-cluster.html

EMSA, & EEA. (2021). *European Maritime Transport Environmental Report 2021.* Publications Office of the European Union. https://www.eea.europa.eu/ds_resolveuid/e800d2b2f0244a11bd2c3b2256961ecb

Gilbert, P., Wilson, P., Walsh, C., & Hodgson, P. (2017). The role of material efficiency to reduce CO2 emissions during ship manufacture: A life cycle approach. *Marine Policy*, *75*, 227–237. https://doi.org/10.1016/j.marpol.2016.04.003

Greening, B., & Azapagic, A. (2012). Domestic heat pumps: Life cycle environmental impacts and potential implications for the UK. *Energy*, *39*(1), 205–217. https://doi.org/10.1016/j.energy.2012.01.028

Greet Database. (2020).

Harahap, F., Nurdiawati, A., Conti, D., Leduc, S., & Urban, F. (2023). Renewable marine fuel production for decarbonised maritime shipping: Pathways, policy measures and transition dynamics. *Journal of Cleaner Production*, *415*, 137906. https://doi.org/10.1016/j.jclepro.2023.137906

Henriksson, P. J. G., Heijungs, R., Dao, H. M., Phan, L. T., Snoo, G. R. de, & Guinée, J. B. (2015). Product carbon footprints and their uncertainties in comparative decision contexts. *PLoS ONE*, *10*(3), e0121221. https://doi.org/10.1371/journal.pone.0121221

ILCD (2010). ILCD Handbook - General guide on LCA - Detailed guidance. https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-General-guide-for-LCA-DETAILED-GUIDANCE-12March2010-ISBN-fin-v1.0-EN.pdf

IMO. (2019). *Safety regulations for different types of ships.* International Maritime Organization. https://www.imo.org/en/OurWork/Safety/Pages/RegulationsDefault.aspx

IRENA. (2021). *A pathway to decarbonise the shipping sector by 2050.* International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Oct/IRENA_Decarbonising_Shipping_2021.pdf?rev=b5dfda5f69e741a4970680a5ced1ac1e

ISO (2006). *ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework*. International Organization for Standardization.

Jain, K. P., Pruyn, J., & Hopman, J. J. (2016). Quantitative assessment of material composition of end-of-life ships using onboard documentation. *Resources, Conservation and Recycling*, *107*, 1–9. https://doi.org/10.1016/j.resconrec.2015.11.017

Jeong, B., Jeon, H., Kim, S., Kim, J., & Zhou, P. (2020). Evaluation of the Lifecycle Environmental Benefits of Full Battery Powered Ships: Comparative Analysis of Marine Diesel and Electricity. *Journal of Marine Science and Engineering*, *8*(8), 580. https://doi.org/10.3390/jmse8080580

Jeong, B., Wang, H [Haibin], Oguz, E., & Zhou, P. (2018). An effective framework for life cycle and cost assessment for marine vessels aiming to select optimal propulsion systems. *Journal of Cleaner Production*, *187*, 111–130. https://doi.org/10.1016/j.jclepro.2018.03.184

Kanchiralla, F. M., Brynolf, S., Malmgren, E., Hansson, J., & Grahn, M. (2022). Life-Cycle Assessment and Costing of Fuels and Propulsion Systems in Future Fossil-Free

Shipping. *Environmental Science & Technology*, *56*(17), 12517–12531. https://doi.org/10.1021/acs.est.2c03016
Kanchiralla, F. M., Brynolf, S., Olsson, T., Ellis, J., Hansson, J., & Grahn, M. (2023). How do variations in ship operation impact the techno-economic feasibility and environmental performance of fossil-free fuels? A life cycle study. *Applied Energy*, *350*, 121773. https://doi.org/10.1016/j.apenergy.2023.121773
Kersey, J., Popovitch, N., & Phadke, A. (2021). Application of rapidly improving battery technology for direct electrification of intraregional container shipping. Advance online publication. https://doi.org/10.21203/rs.3.rs-852125/v1
Korberg, A. D., Brynolf, S., Grahn, M., & Skov, I. R. (2021). Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. *Renewable and Sustainable Energy Reviews*, *142*, 110861. https://doi.org/10.1016/j.rser.2021.110861
Laurent, A., Olsen, S. I., & Hauschild, M. Z. (2012). Limitations of carbon footprint as indicator of environmental sustainability. *Environmental Science & Technology*, *46*(7), 4100–4108. https://doi.org/10.1021/es204163f
Law, L., Foscoli, B., Mastorakos, E., & Evans, S. (2021). A Comparison of Alternative Fuels for Shipping in Terms of Lifecycle Energy and Cost. *Energies*, *14*(24), 8502. https://doi.org/10.3390/en14248502
Lèbre, É., Stringer, M., Svobodova, K., Owen, J. R., Kemp, D., Côte, C., Arratia-Solar, A., & Valenta, R. K. (2020). The social and environmental complexities of extracting energy transition metals. *Nature Communications*, *11*(1), 4823. https://doi.org/10.1038/s41467-020-18661-9
Li, C., Jia, T., Wang, H [Honglei], Wang, X., Negnevitsky, M., Hu, Y., Zhao, G., & Wang, L. (2023). Assessing the prospect of deploying green methanol vehicles in China from energy, environmental and economic perspectives. *Energy*, *263*, 125967. https://doi.org/10.1016/j.energy.2022.125967
Li, C., Jia, T., Wang, S., Wang, X., Negnevitsky, M., Wang, H [Honglei], Hu, Y., Xu, W., Zhou, N., & Zhao, G. (2023). Methanol Vehicles in China: A Review from a Policy Perspective. *Sustainability*, *15*(12), 9201. https://doi.org/10.3390/su15129201
Liang, Z., Ma, X., Lin, H., & Tang, Y. (2011). The energy consumption and environmental impacts of SCR technology in China. *Applied Energy*, *88*(4), 1120–1129. https://doi.org/10.1016/j.apenergy.2010.10.010
Liquid Wind. (2024). *Liquid Wind- eMPowering our Future.* https://www.liquidwind.se/
Louka, P., Finzi, G., Volta, M., & Colbeck, I. (2003). Photochemical smog in South European cities, 185–222. https://doi.org/10.1007/978-3-662-05217-4_9
Malmgren, E. (2023). *Towards Sustainable Shipping: Climate change and other environmental perspectives on carbon-based marine electrofuels and onboard carbon capture* [Doctoral Thesis]. Chalmers University of Technology, Göteborg.
Malmgren, E., Brynolf, S., Fridell, E., Grahn, M., & Andersson, K. (2021). The environmental performance of a fossil-free ship propulsion system with onboard carbon capture – a life cycle assessment of the HyMethShip concept. *Sustainable Energy & Fuels*, *5*(10), 2753–2770. https://doi.org/10.1039/D1SE00105A
Man Energy Solutions. (2021). *The Methanol fuelled MAN B&W LGIM Engine*. https://www.man-es.com/docs/default-source/document-sync-archive/the-methanol-fuelled-man-b-w-lgim-engine-eng.pdf?sfvrsn=36b925d2_7
Methanol Institute. (2023). *Marine Methanol: Future-Proof Shiping Fuel*. https://www.methanol.org/wp-content/uploads/2023/05/Marine_Methanol_Report_Methanol_Institute_May_2023.pdf

Mio, A., Fermeglia, M., & Favi, C. (2022). A critical review and normalization of the life cycle assessment outcomes in the naval sector. Articles description. *Journal of Cleaner Production*, *370*, 133476. https://doi.org/10.1016/j.jclepro.2022.133476
Mondello, G., Salomone, R., Saija, G., Lanuzza, F., & Gulotta, T. M. (2023). Life Cycle Assessment and Life Cycle Costing for assessing maritime transport: a comprehensive literature review. *Maritime Policy & Management*, *50*(2), 198–218. https://doi.org/10.1080/03088839.2021.1972486
Nansai, K., Nakajima, K., Kagawa, S., Kondo, Y., Shigetomi, Y., & Suh, S. (2015). Global mining risk footprint of critical metals necessary for low-carbon technologies: The case of neodymium, cobalt, and platinum in Japan. *Environmental Science & Technology*, *49*(4), 2022–2031. https://doi.org/10.1021/es504255r
Perčić, M., Ančić, I., & Vladimir, N. (2020). Life-cycle cost assessments of different power system configurations to reduce the carbon footprint in the Croatian short-sea shipping sector. *Renewable and Sustainable Energy Reviews*, *131*, 110028. https://doi.org/10.1016/j.rser.2020.110028
Perčić, M., Koričan, M., Jovanović, I., & Vladimir, N. (2024). Environmental and Economic Assessment of Batteries for Marine Applications: Case Study of All-Electric Fishing Vessels. *Batteries*, *10*(1), 7. https://doi.org/10.3390/batteries10010007
Pinto, D. M., Blande, J. D., Souza, S. R., Nerg, A.-M., & Holopainen, J. K. (2010). Plant volatile organic compounds (VOCs) in ozone (O3) polluted atmospheres: The ecological effects. *Journal of Chemical Ecology*, *36*(1), 22–34. https://doi.org/10.1007/s10886-009-9732-3
Prussi, M., Scarlat, N., Acciaro, M., & Kosmas, V. (2021). Potential and limiting factors in the use of alternative fuels in the European maritime sector. *Journal of Cleaner Production*, *291*, 125849. https://doi.org/10.1016/j.jclepro.2021.125849
Quang, P. K., Dong, D. T., & Hai, P. T. T. (2021). Evaluating environmental impacts of an oil tanker using life cycle assessment method. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, *235*(3), 705–717. https://doi.org/10.1177/1475090221989195
Quang, P. K., Dong, D. T., Van, T. V., & Hai, P. T. T. (2020). Greenhouse Gas Emissions of a Cargo Ship from a Life Cycle Perspective. *International Journal of Environmental Science and Development*, *11*(7), 347–351. https://doi.org/10.18178/ijesd.2020.11.7.1274
Ratson Shipbuilding (Ed.). (2023). *General Cargo Vessels: A Comprehensive Guide - Articles - Ship Building Shipyard Indonesia - Ratson*. https://www.ratson.com/id/home/infocenterdetail/id/80
Regulation (EU) 2015/757. Regulation (EU) 2015/757 of the European Parliament and of the Council of 29 April 2015 on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport, and amending Directive 2009/16/EC. *Official Journal of the European Union*. http://data.europa.eu/eli/reg/2015/757/oj
Regulation (EU) 2021/1119. Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'). *Official Journal of the European Union*. http://data.europa.eu/eli/reg/2021/1119/oj
Regulation (EU) 2023/1805. Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC. *Official Journal of the European Union*. http://data.europa.eu/eli/reg/2023/1805/oj

Regulation (EU) 2023/957. Regulation (EU) 2023/957 of the European Parliament and of the Council of 10 May amending Regulation (EU) 2015/757 in order to provide for the inclusion of maritime transport activities in the EU Emissions Trading System and for the monitoring, reporting and verification of emissions of additional greenhouse gases and emissions from additional ship types. *Official Journal of the European Union*. http://data.europa.eu/eli/reg/2023/957/oj

S&P Global. (2024a). *Data from seaweb, analyzed by Elin Malmgren*. https://maritime.ihs.com/EntitlementPortal/Home/Index?autoLogin=True

S&P Global. (2024b). *My Home – S&P Global - Home*. https://maritime.ihs.com/Home/Index

Sahu, S., Kumar, P., & Dhar, A. (2023). Combustion, performance, and emissions characteristics of methanol-fueled engines. In N. Kumar, K. Mathiyazhagan, R. Sreedharan, & A. Kalam (Eds.), *Advancement in oxygenated fuels for sustainable development: Feedstocks and precursors for catalysts synthesis* (pp. 263–283). Elsevier. https://doi.org/10.1016/B978-0-323-90875-7.00008-3

Sala, S., Crenna, E., Pant, R., & Secchi, M. (2017). *Global normalisation factors for the environmental footprint and Life Cycle Assessment*. *EUR, Scientific and technical research series: Vol. 28984*. Publications Office of the European Union.

Saouter, E., Biganzoli, F., Pant, R., Sala, S., & Versteeg, D. (2019). Using REACH for the EU Environmental Footprint: Building a Usable Ecotoxicity Database, Part I. *Integrated Environmental Assessment and Management*, *15*(5), 783–795. https://doi.org/10.1002/ieam.4168

Schreiber, A., Marx, J., & Zapp, P. (2019). Comparative life cycle assessment of electricity generation by different wind turbine types. *Journal of Cleaner Production*, *233*, 561–572. https://doi.org/10.1016/j.jclepro.2019.06.058

Schwartz, H., Solakivi, T., & Gustafsson, M. (2022). Is There Business Potential for Sustainable Shipping? Price Premiums Needed to Cover Decarbonized Transportation. *Sustainability*, *14*(10), 5888. https://doi.org/10.3390/su14105888

Seithe, G. J., Bonou, A., Giannopoulos, D., Georgopoulou, C. A., & Founti, M. (2020). Maritime Transport in a Life Cycle Perspective: How Fuels, Vessel Types, and Operational Profiles Influence Energy Demand and Greenhouse Gas Emissions. *Energies*, *13*(11), 2739. https://doi.org/10.3390/en13112739

Siemens. (2018). *Sigentics M generators, PDLD-B10133-00-7600*. https://assets.new.siemens.com/siemens/assets/api/uuid:ec46167cfbe7581cbaaa5ed48c0de4ffec659018/455-180428-ws-sigentics-m-d-ak-180801-ohneanmerk.pdf

Styhre, L., Jivén, K., Svedberg, S., Hansson, J., Prestley, M., Storm, B., Särnbratt, M., Grahn, D., Malmgren, E., Hjort, A., Parsmo, R., Mikoliūnas, M., & Mickevičius, L. (2024). *Role of Port Authorities in green energy supply for transports chains: The way towards a green bunkering and charging strategy for ports and emission free inland waterways connecting a seaport with the hinterland*. Draft Report v.03.

Swedish Environmental Protection Agency. (2023a). *Emissions of greenhouse gases from domestic transport by type of greenhouse gas and mode of transport. Year 1990 - 2022*. https://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__MI__MI0107/MI0107InTranspNN/

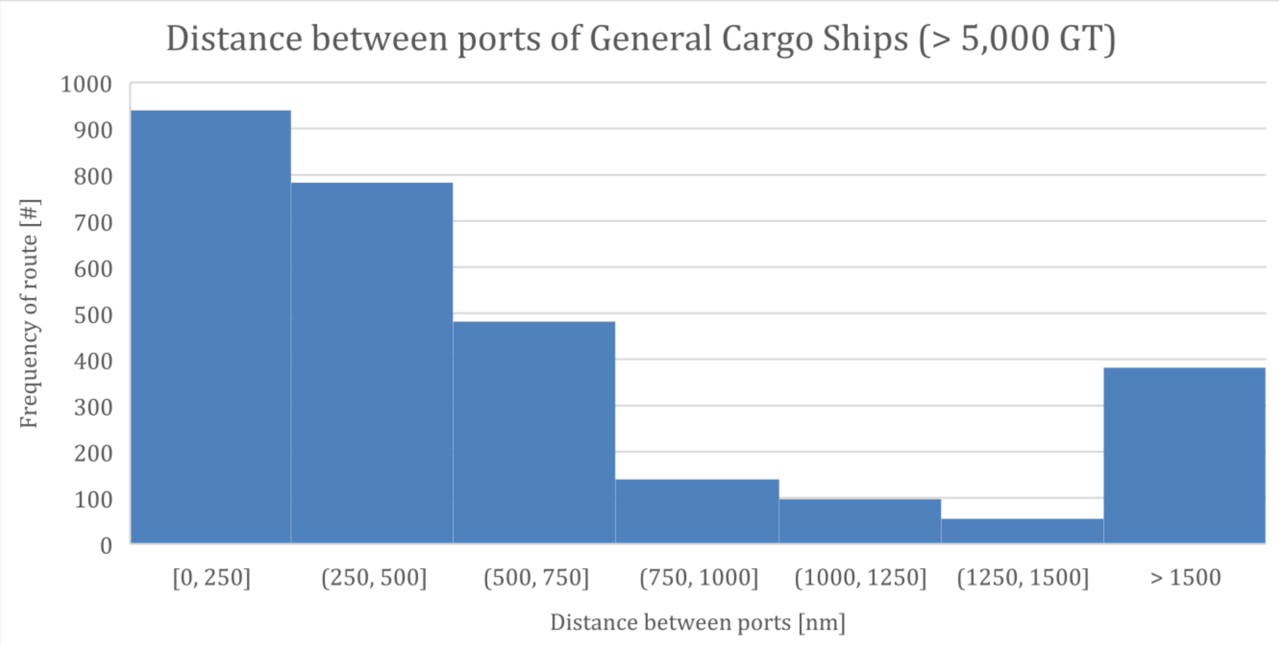
Swedish Environmental Protection Agency. (2023b). *Emissions of greenhouse gases from international transport by greenhouse gas, activity and year*. https://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__MI__MI0107/MI0107UtrikesTransNN/table/tableViewLayout1/

Transport & Environment. (2021). *FuelEU Maritime: Shipping required to switch fuel but without clear path to sustainable alternatives*.

https://www.transportenvironment.org/wp-content/uploads/2021/08/FuelEU-Maritime.pdf
Transport & Environment. (2022). *Climate Impacts of Exemptions to EU's Shipping Proposals.*
Verones, F., Moran, D., Stadler, K., Kanemoto, K., & Wood, R. (2017). Resource footprints and their ecosystem consequences. *Scientific Reports*, *7*, 40743. https://doi.org/10.1038/srep40743
Wang, Z., Dong, B., Li, M., Ji, Y., & Han, F. (2024). Configuration of Low-Carbon fuels green marine power systems in diverse ship types and Applications. *Energy Conversion and Management*, *302*, 118139. https://doi.org/10.1016/j.enconman.2024.118139
Xing, H., Stuart, C., Spence, S., & Chen, H. (2021). Alternative fuel options for low carbon maritime transportation: Pathways to 2050. *Journal of Cleaner Production*, *297*, 126651. https://doi.org/10.1016/J.JCLEPRO.2021.126651
Ytreberg, E., Hansson, K., Hermansson, A. L., Parsmo, R., Lagerström, M., Jalkanen, J.-P., & Hassellöv, I.-M. (2022). Metal and PAH loads from ships and boats, relative other sources, in the Baltic Sea. *Marine Pollution Bulletin*, *182*, 113904. https://doi.org/10.1016/j.marpolbul.2022.113904
Zhang, Y., Chang, Y., Wang, C., Fung, J. C. H., & Lau, A. K. H. (2022). Life ‐ cycle energy and environmental emissions of cargo ships. *Journal of Industrial Ecology*, *26*(6), 2057–2068. https://doi.org/10.1111/jiec.13293
Zincir, B. A., & Arslanoglu, Y. (2024). Comparative Life Cycle Assessment of Alternative Marine Fuels. *Fuel*, *358*, 129995. https://doi.org/10.1016/j.fuel.2023.129995

Appendix

A.1: Distribution of distances between port of general cargo ships (> 5,000 GT). Source: Styhre et al. (2024) & S&P Global (2024a)



A.2: Distribution of size of general cargo ships (> 5,000 GT). Source: Styhre et al. (2024) & S&P Global (2024a)

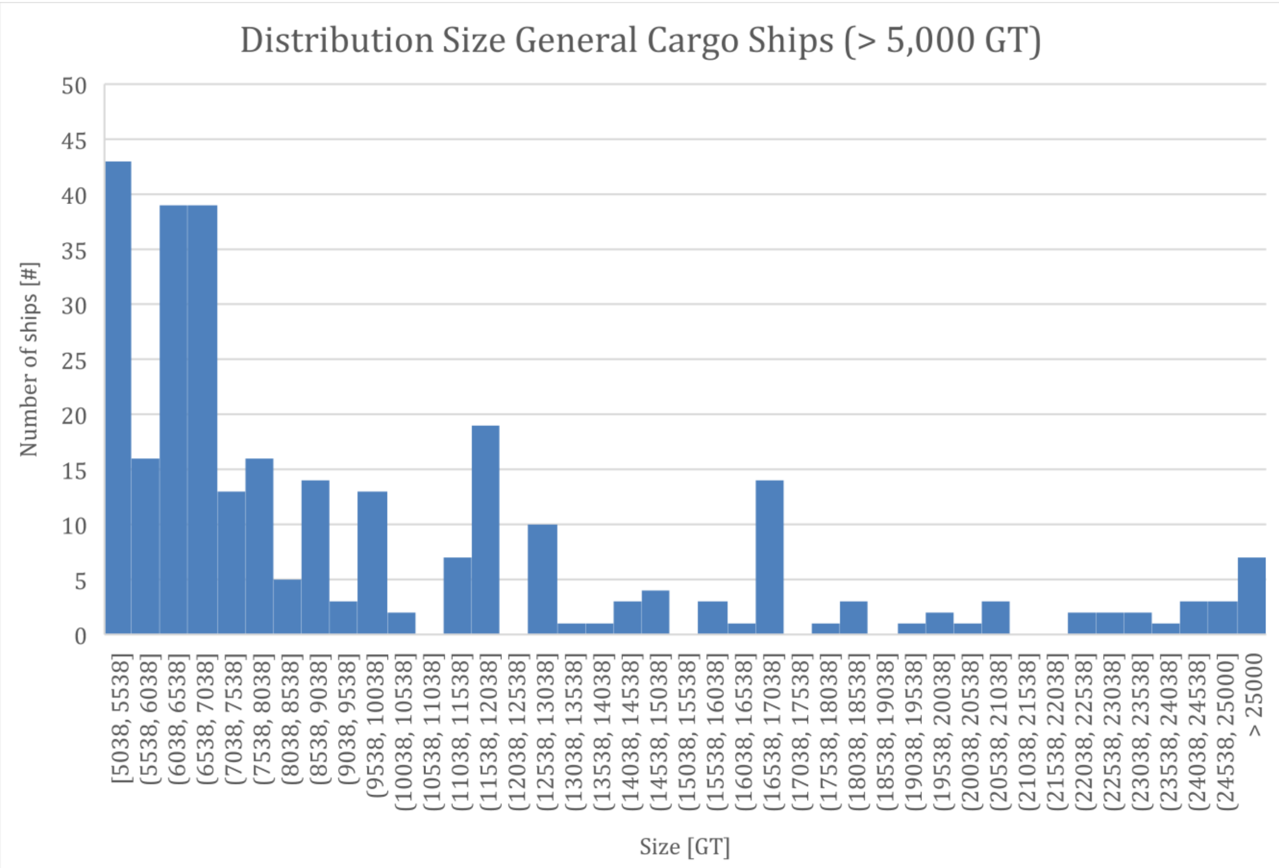


Table A.3: Unit data processes – Case 1

	Flow properties	Amount	Unit	Reference
Vessel				
Reference flow				
Ship building	Product	1	Item	Kanchiralla et al. (2023); Jain et al. (2016)
Inflow				
Alkyd paint, white, without solvent in 60% solution state	Product	17.70	tons	Ecoinvent 3.8 (market for alkyd paint, white, without solvent, in 60% solution state | alkyd paint, white, without solvent, in 60% solution state | Cutoff, S)
Aluminium, wrought alloy	Product	7.35	tons	Ecoinvent 3.8 (market for aluminium, wrought alloy | aluminium, wrought alloy | Cutoff, S)
Asbestos, crysotile type	Product	12.65	tons	Ecoinvent 3.8 (market for asbestos, crysotile type | asbestos, crysotile type | Cutoff, S)
Bronze	Product	2.31	tons	Ecoinvent 3.8 (market for bronze | bronze | Cutoff, S)
Cable, unspecified	Product	10.88	tons	Ecoinvent 3.8 (market for cable, unspecified | cable, unspecified | Cutoff, S)
Copper, cathode	Product	2.52	tons	Ecoinvent 3.8 (market for copper, cathode | copper, cathode | Cutoff, S)
Electronic component, machinery, unspecified	Product	6.8	Item	Ecoinvent 3.8 (market for electronic component machinery, unspecified | electronic component machinery, unspecified | Cutoff, S)
Glass wool mat	Product	12.65	tons	Ecoinvent 3.8 (market for glass wool mat | glass wool mat | Cutoff, S)
Electricity (EU-27)	Product	449	MWh	IDEMAT 2021 (Electricity EU-27)
Polyethylene, low density, granulate	Product	4.5	tons	Ecoinvent 3.8 (market for polyethylene, low density, granulate | polyethylene, low density, granulate | Cutoff, S)
Polypropylene, granulate	Product	4.5	tons	Ecoinvent 3.8 (market for polypropylene, granulate | polypropylene, granulate | Cutoff, S)
Polystrene, general purpose	Product	4.5	tons	Ecoinvent 3.8 (market for polystyrene, general purpose | polystyrene, general purpose | Cutoff, S)
Polyvinylchloride, bulk polymerized	Product	4.5	tons	Ecoinvent 3.8 (market for polyvinylchloride, bulk polymerised | polyvinylchloride, bulk polymerised | Cutoff, S)
Reinforcing steel	Product	1399	tons	Ecoinvent 3.8 (market for reinforcing steel | reinforcing steel | Cutoff, S)
Sanitary ceramics	Product	12.65	tons	Ecoinvent 3.8 (market for sanitary ceramics | sanitary ceramics | Cutoff, S)
Zinc	Product	0.68	tons	Ecoinvent 3.8 (market for zinc | zinc | Cutoff, S)
SCR – Component				
Reference flow				
SCR, component	Product	100	kg	Jeong et al. (2018)
Inflow				

Steel, chromium steel 18/8	Product	99.88	kg	Ecoinvent 3.8 (market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S)
Titanium dioxide	Product	0.12	kg	Ecoinvent 3.8 (market for titanium dioxide | titanium dioxide | Cutoff, S)
SCR – Component replacement				
Reference flow				
SCR, component replacement	Product	100	kg	Jeong et al. (2018)
Inflow				
Steel, chromium steel 18/8	Product	99.88	kg	Ecoinvent 3.8 (market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S)
Titanium dioxide	Product	0.12	kg	Ecoinvent 3.8 (market for titanium dioxide | titanium dioxide | Cutoff, S)
Alternator				
Reference flow				
Alternator, component	Product	100	kg	Greet Database (2020)
Inflow				
Aluminium, primary, ingot	Product	36.10	kg	Ecoinvent 3.8 (market for aluminium, primary, ingot | aluminium, primary, ingot | Cutoff, S)
Steel, chromium steel 18/8	Product	27.80	kg	Ecoinvent 3.8 (market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S)
Wire drawing, copper	Product	36.10	kg	Ecoinvent 3.8 (market for wire drawing, copper | wire drawing, copper | Cutoff, S)
Heat Pump				
Reference flow				
Heat Pump, component	Product	100	kg	Greening and Azapagic (2012)
Inflow				
Aluminium, primar, ingot	Product	22.77	kg	Ecoinvent 3.8 (market for aluminium, primary, ingot | aluminium, primary, ingot | Cutoff, S)
Chromium	Product	0.88	kg	Ecoinvent 3.8 (market for chromium | chromium | Cutoff, S)
Lead	Product	1.02	kg	Ecoinvent 3.8 (market for chromium | chromium | Cutoff, S)
Nickel, class 1	Product	1.02	kg	Ecoinvent 3.8 (market for nickel, class 1 | nickel, class 1 | Cutoff, S)
Polyethylene, high density, granulate	Product	3.36	kg	Ecoinvent 3.8 (polyethylene production, high density, granulate | polyethylene, high density, granulate | Cutoff, S)
Polyvinylchloride, suspension polymerised	Product	25.4	kg	Ecoinvent 3.8 (polyvinylchloride production, suspension polymerisation | polyvinylchloride, suspension polymerised | Cutoff, S)
Steel, chromium steel 18/8	Product	33	kg	Ecoinvent 3.8 (steel production, electric, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S)
Wire drawing, copper	Product	12.55	kg	Ecoinvent 3.8 (wire drawing, copper | wire drawing, copper | Cutoff, S)
Operation MGO [kg fuel/kWh Proeller Output]				
Reference flow				

Operation for 1 kWh Propeller Output	Product	1	kWh	
Inflow				
Diesel, low-sulfur	Product	176	g	Ecoinvent 3.8 (diesel production, low-sulfur, petroleum refinery operation | diesel, low-sulfur | Cutoff); Kanchiralla et al. (2023)
Urea	Product	9	g	Ecoinvent 3.8 (market for urea | urea | Cutoff, U). It is assumed that the urea is produced in Europe; Kanchiralla et al. (2023)
Output				
NH_3	Emission to air	0.05	g	Kanchiralla et al. (2023)
BC	Emission to air	0.005	g	Kanchiralla et al. (2023)
CO_2	Emission to air	568	g	Kanchiralla et al. (2023)
CO	Emission to air	1	g	Kanchiralla et al. (2023)
N_2O	Emission to air	0.03	g	Kanchiralla et al. (2023)
CH_4	Emission to air	0.01	g	Kanchiralla et al. (2023)
NO_x	Emission to air	2.6	g	Kanchiralla et al. (2023)
PM_{10}	Emission to air	0.4	g	Kanchiralla et al. (2023)
SO_x	Emission to air	0.343	g	Kanchiralla et al. (2023)

Table A.4: System processes used as background data in the life-cycle assessment – Case 1

	Flow properties	Amount	Unit	Reference
Marine gas oil production				
Reference flow				
Diesel, low-sulfur	Product	1	kg	Ecoinvent 3.8 (diesel production, low-sulfur, petroleum refinery operation | diesel, low-sulfur | Cutoff).
Urea production				
Reference flow				
Urea	Product	1	kg	Ecoinvent 3.8 (market for urea | urea | Cutoff, U).
Maintenance				
Reference flow				
Maintenance, bulk carrier	Product	1	Item	Ecoinvent 3.8 (maintenance, bulk carrier, for dry goods | maintenance, bulk carrier, for dry goods | Cutoff, U)
Main Engine				
Reference flow				
Marine engine	Product	1	Item	Ecoinvent 3.8 (market for marine engine | marine engine | Cutoff, U)

Table A.5: Unit data processes – Case 2

	Flow properties	Amount	Unit	Reference
Vessel				
Reference flow				
Ship building	Product	1	Item	Kanchiralla et al. (2023); Jain et al. (2016)
Inflow				
Alkyd paint, white, without solvent in 60% solution state	Product	17.70	tons	Ecoinvent 3.8 (market for alkyd paint, white, without solvent, in 60% solution state | alkyd paint, white, without

				solvent, in 60% solution state | Cutoff, S)
Aluminium, wrought alloy	Product	7.35	tons	Ecoinvent 3.8 (market for aluminium, wrought alloy | aluminium, wrought alloy | Cutoff, S)
Asbestos, crysotile type	Product	12.65	tons	Ecoinvent 3.8 (market for asbestos, crysotile type | asbestos, crysotile type | Cutoff, S)
Bronze	Product	2.31	tons	Ecoinvent 3.8 (market for bronze | bronze | Cutoff, S)
Cable, unspecified	Product	10.88	tons	Ecoinvent 3.8 (market for cable, unspecified | cable, unspecified | Cutoff, S)
Copper, cathode	Product	2.52	tons	Ecoinvent 3.8 (market for copper, cathode | copper, cathode | Cutoff, S)
Electronic component, machinery, unspecified	Product	6.8	Item	Ecoinvent 3.8 (market for electronic component machinery, unspecified | electronic component machinery, unspecified | Cutoff, S)
Glass wool mat	Product	12.65	tons	Ecoinvent 3.8 (market for glass wool mat | glass wool mat | Cutoff, S)
Electricity (EU-27)	Product	449	MWh	IDEMAT 2021 (Electricity EU-27)
Polyethylene, low density, granulate	Product	4.5	tons	Ecoinvent 3.8 (market for polyethylene, low density, granulate | polyethylene, low density, granulate | Cutoff, S)
Polypropylene, granulate	Product	4.5	tons	Ecoinvent 3.8 (market for polypropylene, granulate | polypropylene, granulate | Cutoff, S)
Polystrene, general purpose	Product	4.5	tons	Ecoinvent 3.8 (market for polystyrene, general purpose | polystyrene, general purpose | Cutoff, S)
Polyvinylchloride, bulk polymerized	Product	4.5	tons	Ecoinvent 3.8 (market for polyvinylchloride, bulk polymerised | polyvinylchloride, bulk polymerised | Cutoff, S)
Reinforcing steel	Product	1399	tons	Ecoinvent 3.8 (market for reinforcing steel | reinforcing steel | Cutoff, S)
Sanitary ceramics	Product	12.65	tons	Ecoinvent 3.8 (market for sanitary ceramics | sanitary ceramics | Cutoff, S)
Zinc	Product	0.68	tons	Ecoinvent 3.8 (market for zinc | zinc | Cutoff, S)
SCR – Component				
Reference flow				
SCR, component	Product	100	kg	Jeong et al. (2018)
Inflow				
Steel, chromium steel 18/8	Product	99.88	kg	Ecoinvent 3.8 (market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S)
Titanium dioxide	Product	0.12	kg	Ecoinvent 3.8 (market for titanium dioxide | titanium dioxide | Cutoff, S)
SCR – Component replacement				
Reference flow				
SCR, component replacement	Product	100	kg	Jeong et al. (2018)
Inflow				
Steel, chromium steel 18/8	Product	99.88	kg	Ecoinvent 3.8 (market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S)

Titanium dioxide	Product	0.12	kg	Ecoinvent 3.8 (market for titanium dioxide | titanium dioxide | Cutoff, S)
Alternator				
Reference flow				
Alternator, component	Product	100	kg	GREET database 2020
Inflow				
Aluminium, primary, ingot	Product	36.10	kg	Ecoinvent 3.8 (market for aluminium, primary, ingot | aluminium, primary, ingot | Cutoff, S)
Steel, chromium steel 18/8	Product	27.80	kg	Ecoinvent 3.8 (market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S)
Wire drawing, copper	Product	36.10	kg	Ecoinvent 3.8 (market for wire drawing, copper | wire drawing, copper | Cutoff, S)
Heat Pump				
Reference flow				
Heat Pump, component	Product	100	kg	Greening and Azapagic (2012)
Inflow				
Aluminium, primar, ingot	Product	22.77	kg	Ecoinvent 3.8 (market for aluminium, primary, ingot | aluminium, primary, ingot | Cutoff, S)
Chromium	Product	0.88	kg	Ecoinvent 3.8 (market for chromium | chromium | Cutoff, S)
Lead	Product	1.02	kg	Ecoinvent 3.8 (market for chromium | chromium | Cutoff, S)
Nickel, class 1	Product	1.02	kg	Ecoinvent 3.8 (market for nickel, class 1 | nickel, class 1 | Cutoff, S)
Polyethylene, high density, granulate	Product	3.36	kg	Ecoinvent 3.8 (polyethylene production, high density, granulate | polyethylene, high density, granulate | Cutoff, S)
Polyvinylchloride, suspension polymerised	Product	25.4	kg	Ecoinvent 3.8 (polyvinylchloride production, suspension polymerisation | polyvinylchloride, suspension polymerised | Cutoff, S)
Steel, chromium steel 18/8	Product	33	kg	Ecoinvent 3.8 (steel production, electric, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S)
Wire drawing, copper	Product	12.55	kg	Ecoinvent 3.8 (wire drawing, copper | wire drawing, copper | Cutoff, S)
Tank eMeOH				
Reference Flow				
Tank eMeOH	Product	1	kg	Note: only additional size and weight between tank of Case 1 is considered
Inflow				
Steel, chromium steel 18/8	Product	1	kg	Ecoinvent 3.8 (steel production, electric, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S)
Operation eMeOH [kg fuel/kWh Proeller Output]				
Reference flow				
Operation for 1 kWh Propeller Output	Product	1	kWh	
Inflow				
eMeOH	Product	358	g	
Pilot fuel	Product	9	g	Ecoinvent 3.8 (diesel production, low-sulfur, petroleum refinery operation |

				diesel, low-sulfur | Cutoff); Kanchiralla et al. (2023)
Urea	Product	3.36	g	Ecoinvent 3.8 (market for urea | urea | Cutoff, U); Kanchiralla et al. (2023)
Output				
NH_3	Emission to air	0.025	g	Kanchiralla et al. (2023)
BC	Emission to air	0.0016	g	Kanchiralla et al. (2023)
CO_2	Emission to air	520	g	Kanchiralla et al. (2023)
CO	Emission to air	0.17	g	Kanchiralla et al. (2023)
N_2O	Emission to air	0.003	g	Kanchiralla et al. (2023)
CH_4	Emission to air	0.01	g	Kanchiralla et al. (2023)
NO_x	Emission to air	2.6	g	Kanchiralla et al. (2023)
PM_{10}	Emission to air	0.093	g	Kanchiralla et al. (2023)
SO_x	Emission to air	0.017	g	Kanchiralla et al. (2023)
Production of eMeOH				
Reference flow				
eMeOH	Product	1	kg	Malmgren et al. (2021)
Input				
CO2 supply	Product	1.375	kg	Deutz and Bardow (2021)
Renewable electricity	Product	5.24	MJ	NEED (electricity, at offshore wind park 160MW | Scenario: Today)
Hydrogen supply	Product	0.189	kg	Delpierre et al. (2021)
Methanol factory	Product	3.7037E-11	Item	Ecoinvent 3.8 (market for methanol factory | methanol factory | Cutoff, U)
Output				
CO2	Emission to air	7.65E-6	kg	Ecoinvent 3.8
CO	Emission to air	6.9E-7	kg	Ecoinvent 3.8
Methanol	Emission to air	0.00172	kg	Ecoinvent 3.8
Carbon dioxide capture – for CO_2 supply				
Reference flow				
CO2 supply	Product	1	kg	Deutz and Bardow (2021)
Input				
Renewable electricity	Product	0.875	kWh	NEED (electricity, at offshore wind park 160MW | Scenario: Today)
CO2	Elementary flow	-1	kg	Note: is accounted for as a negative input
Monoethanolamine	Product	3	g	Ecoinvent 3.8 (ethanolamine production | monoethanolamine | Cutoff, S)
DAC construction	Infrastructure	1	Item	Ecoinvent 3.8
Electrolysis – for hydrogen supply				
Reference flow				
Hydrogen supply	Product	1	kg	Delpierre et al. (2021)
Input				
Alkaline electrolyser contruction	Product	0.0003	Item	Delpierre et al. (2021)
Renewable electricity	Product	50	kWh	NEED (electricity, at offshore wind park 160MW | Scenario: Today)
Potassium hydroxide	Product	0.002	kg	Ecoinvent 3.8 (potassium hydroxide production | potassium hydroxide | Cutoff, U – RER)
Water, deionised	Product	10	kg	Ecoinvent 3.8 (market for water, deionised | water, deionised | Cutoff, S – Europe without Switzerland)

Table A.6: System processes used as background data in the life-cycle assessment – Case 2

	Flow properties	Amount	Unit	Reference
Pilot fuel production				
Reference flow				
Diesel, low-sulfur	Product	1	kg	Ecoinvent 3.8 (diesel production, low-sulfur, petroleum refinery operation | diesel, low-sulfur | Cutoff).
Urea production				
Reference flow				
Urea	Product	1	kg	Ecoinvent 3.8 (market for urea | urea | Cutoff, U). It is assumed that the urea is produced in Europe.
Maintenance				
Reference flow				
Maintenance, bulk carrier	Product	1	Item	Ecoinvent 3.8 (maintenance, bulk carrier, for dry goods | maintenance, bulk carrier, for dry goods | Cutoff, U)
Main Engine				
Reference flow				
Marine engine	Product	1	Item	Ecoinvent 3.8 (market for marine engine | marine engine | Cutoff, U)

Table A.7: Values to estimate mass and volume of propulsion system. Source: Kanchiralla et al. (2023)

	m³/kW	**kg/kW**
Engine	0.0229	13.00
Electric Motor (kW)	0.0050	2.50
Alternator (kW)	0.0050	2.50
Heat Pump (kW)	0.0657	2.50
Gear Box (kW)	0.0013	0.80
Battery (kWh)	0.0020	5.00
	m³/GJ	**kg/GJ (with fuel)**
MeOH tank	0.07	57.54
MGO tank	0.02	27.26

A.8: Boxplot of Capacity Factor of General Cargo Ships. Source: MRV data

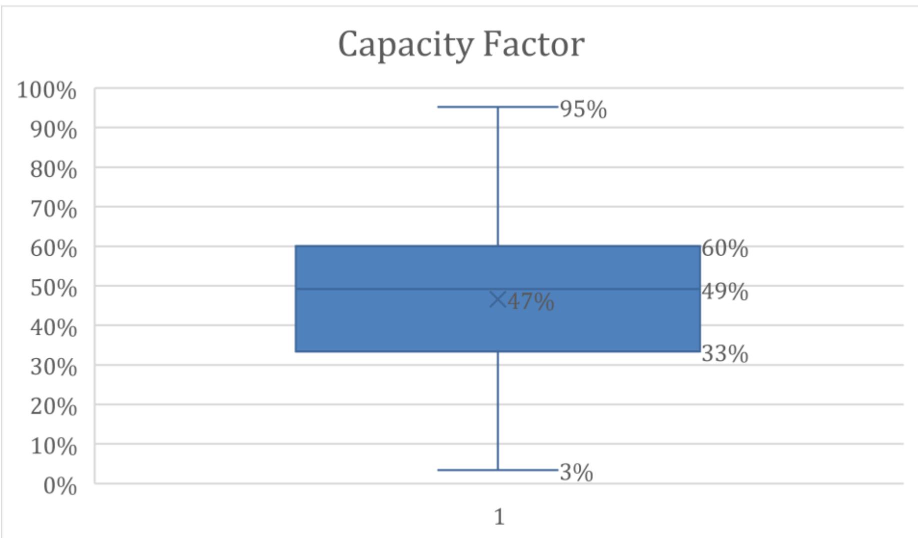


Table A.9: Characterization, normalization and weighting results for Case 1 based on EF 3.0

Impact category	Reference unit	Characterization results	Normalized results	Weighted results
Acidification	mol H+ eq.	50,168.89	903.04	55.99
Climate change	kg CO2 eq.	8,903,581.69	1,099.59	231.57
Ecotoxicity, freshwater	CTUe	66,941,339.45	1,568.44	30.11
Eutrophication, freshwater	kg P eq.	179.24	111.54	3.12
Eutrophication, marine	kg N eq.	14,956.36	765.17	22.65
Human toxicity, cancer	CTUh	0.00	85.38	1.82
Human toxicity, non-cancer	CTUh	0.02	84.50	1.55
Ozone depletion	kg CFC11 eq.	2.00	37.28	2.35
Particulate matter	disease inc.	0.48	800.35	71.71
Photochemical ozone formation	kg NMVOC eq.	43,226.94	1,064.68	50.89
Resource use, fossils	MJ	126,012,731.19	1,938.08	161.25
Resource use, minerals and metals	kg Sb eq.	10.35	162.67	12.28

Table A.10: Characterization, normalization and weighting results for Case 2 based on EF 3.0

Impact category	Reference unit	Characterization results	Normalized results	Weighted results
Acidification	mol H+ eq.	38,344.33	690.20	42.79
Climate change	kg CO2 eq.	1,665,249.55	205.66	43.31
Ecotoxicity, freshwater	CTUe	66,692,398.42	1,562.60	30.00
Eutrophication, freshwater	kg P eq.	153.50	95.52	2.67
Eutrophication, marine	kg N eq.	14,587.45	746.29	22.09
Human toxicity, cancer	CTUh	0.00	150.41	3.20
Human toxicity, non-cancer	CTUh	0.06	244.70	4.50
Ozone depletion	kg CFC11 eq.	1.06	19.67	1.24
Particulate matter	disease inc.	0.20	342.43	30.68
Photochemical ozone formation	kg NMVOC eq.	42,086.64	1,036.59	49.55
Resource use, fossils	MJ	69,728,967.55	1,072.43	89.23
Resource use, minerals and metals	kg Sb eq.	15.47	243.02	18.35

Table A.11: Well-to-wake percentage contribution of process' groups to the life-cycle performance of the "Operation of a general cargo ship (< 5,000 GT) for one years" of Case 1 and Case 2

	1. Shipbuilding		2. Ship Operation		3. Ship Maintenance and Replacements		4. Fuel Production	
Impact category	**Case 1**	**Case 2**	**Case 1**	**Case 2**	**Case 1**	**Case 2**	**Case 1**	**Case 2**
Acidification	1.00%	1.31%	68.63%	69.25%	0.29%	0.38%	30.08%	29.06%
Climate change	1.08%	5.71%	84.26%	55.88%	0.18%	0.95%	14.48%	37.47%
Ecotoxicity, freshwater	5.82%	5.77%	2.80%	1.08%	0.63%	0.64%	90.75%	92.52%
Eutrophication, freshwater	29.29%	36.72%	17.59%	5.58%	2.17%	3.44%	50.95%	54.26%
Eutrophication, marine	0.72%	0.73%	87.01%	88.50%	0.12%	0.13%	12.15%	10.64%
Human toxicity, cancer	48.85%	28.13%	5.69%	4.43%	3.87%	2.19%	41.59%	65.24%
Human toxicity, non-cancer	16.49%	5.50%	8.33%	1.07%	2.15%	0.74%	73.03%	92.69%
Ozone depletion	0.27%	0.50%	1.51%	1.06%	0.05%	0.09%	98.18%	98.35%
Particulate matter	1.55%	3.58%	80.52%	62.54%	0.20%	0.47%	17.73%	33.41%
Photochemical ozone formation	0.99%	1.01%	77.97%	78.78%	2.13%	2.18%	18.92%	18.03%
Resource use, fossils	0.87%	1.56%	2.91%	1.96%	0.12%	0.22%	96.10%	96.26%
Resource use, minerals and metals	61.78%	41.47%	22.74%	5.69%	1.28%	0.85%	14.20%	51.99%

Table A.12: Sensitivity Analysis of Capacity Factor: Characterization tables of Case 1 and Case 2

		Baseline – 49%		V1CF – 30%		V2CF – 68%	
Impact Category	**Reference Unit**	**Case 1 – MGO**	**Case 2 – eMeOH**	**Case 1 – MGO**	**Case 2 – eMeOH**	**Case 1 – MGO**	**Case 2 – eMeOH**
Acidification (x10^3)	Mol H+ eq.	0.44	0.34	0.72	0.55	0.32	0.24
Climate change (x10^3)	kg CO_2 eq.	78.59	14.70	128.36	24.01	56.63	10.59
Ecotoxicity, freshwater	CTU_e	0.59	0.59	0.97	0.96	0.43	0.42
Eutrophication, freshwater (x10^6)	kg P eq.	1.58	1.36	2.58	2.21	1.14	0.98
Eutrophication, marine (x10^3)	CTU_h	0.13	0.13	0.22	0.21	0.10	0.09
Human toxicity, cancer (x10^9)	CTU_h	0.01	0.02	0.02	0.04	0.01	0.02
Human toxicity, non-cancer (x10^9)	kg CFC-11 eq.	0.17	0.50	0.28	0.81	0.12	0.36
Ozone depletion (x10^9)	Disease inc.	17.65	9.31	28.83	15.21	12.72	6.71
Particulate matter (x10^9)	MJ	4.20	1.80	6.87	2.94	3.03	1.30
Photochemical ozone formation (x10^{-3})	kg Sb eq.	0.38	0.37	0.62	0.61	0.27	0.27

Table A.13: Share of fossil fuels and eMeOH necessary to meet required emission reduction from FuelEU maritime regulation for the general cargo fleet calling Swedish ports in 2022 WITHOUT applying the RFNBO multiplier