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Life Cycle Assessment of Fuel Choices for Marine Vessels

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MASTER THESIS

for

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Life cycle assessment of fuel choices for marine vessels

Livsløpsvurdering av drivstoffvalg for marine fartøy

Background and objective

Shipping and other marine operations are growing quickly, contributing to environmental impacts through climate change, air and ocean pollution. At the same time, there is a focus on reducing these impacts through modifications in ship design, operation, fuel choice, and dedicated technical changes. Different vessels are designed for specific applications, whether it is coastal traffic, supply ships, or long-distance freight. The operational characteristics depend on these applications, and the environmental impact depend partly on the location and hence proximity of safeguard subjects.

DNV has for many years worked to understand and quantify emissions from shipping, the options available for mitigation, and the possible impacts from such emissions. DNV possesses in-depth knowledge of world fleet operations and emissions, and of individual ship and engine operation and performance. Recent findings have indicated that available technical and operational measures for CO2 mitigation from shipping may not contribute sufficiently to reaching the global 2degree target, and this has led to an increased interest in alternative, low carbon fuels, including LNG and Bio-gas, Bio-diesel and crude plant oils for marine applications in a long-term perspective.

The objective of this thesis is to develop and illustrate a life-cycle based approach to evaluating the environmental impact of fuel choice for different marine vessels and their typical operations. This approach should be useful for making trade-off decisions and illustrating the sensitivity of multiple environmental impacts to fuel choice, operational variables (such as full or partial load), etc for specified vessels. It should be possible to apply this to different vessel types. The scope of this work is to be further refined after studying the literature in discussion with the supervisor and the industrial partner. Specific choices regarding what operations, vessels, fuels and impacts to consider will be selected in this process, after an initial evaluation of a specific vessel and its typical operations.

The following questions are to be considered:

1. What are the environmental impacts considered important for ships, and pertinent policies and regulations? Relate this to the choice of a suitable impact assessment method.
2. What are the findings of the current literature on the life-cycle impacts and climate effects of ships? What is the contribution of different life cycle stages?
3. How can less-important life cycle stages be included in a similar manner in order to simply the assessment of different ship types?
4. How can knowledge on energy efficiency and combustion-related emissions of ship motors, dependent on operations, the type of ship and engine, and the fuel, be included in the assessment?
5. Is there a trade-off between multiple environmental impacts? What are the factors that might influence the preferred fuel for vessels?
6. What are the most promising low-carbon fuel alternatives for marine application?

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

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The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

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☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 16. January 2013

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Preface

This master's thesis is submitted in partial fulfillment of the requirements for the Master of Science degree in Energy and Environment. The work was conducted at the Department of Energy and Process Engineering and at the Industrial Ecology Programme at the Norwegian University of Science and Technology (NTNU).

The study has been a collaboration project between the Industrial Ecology Department at NTNU and DNV.

I will first of all thank my academic supervisor Prof. Edgar Hertwich and co-supervisor at DNV, Christos Chryssakis for their indispensable help and guidance. I will also express my gratitude to PhD Evert Bouman and Post-doc Ryan M. Bright at the Industrial Ecology Programme for their assistance and clarifying comments.

During the writing of my thesis, I have had the privilege of sitting at the Research and Development department at DNV. I would like to thank them all for a positive and educational stay.

I thank Prof. Anders H. Strømman for introducing me to LCA and by so bringing enthusiasm and motivation for continued studies.

I cannot express the value of the received support from fellow students, family, friends and boyfriend the past five years. I'm grateful for all the memories we have shared along this path to graduation.

Martha Marie Øberg
Trondheim, June 2013

Abstract

Transporting 80% for the total volume of goods in the world, shipping is currently the backbone of the global economy. The global fleet consists of multiple types of vessels, which delivers various forms of services. As the global economy grows, and the shipping fleet with it, the concern in local and international communities of the environmental impact of shipping has increased.

Introduction of alternative fuels as a step towards a more environmental friendly shipping industry has been evaluated. The goal of this study has been to develop and illustrate a life-cycle based approach to evaluate the environmental impact of fuel choice for different marine vessels and their typical operational pattern.

The Life Cycle Assessment performed evaluates six fuel choices (heavy fuel oil(HFO), marine diesel oil/marine gas oil (MDO/MGO), liquefied natural gas (LNG), methanol, dimethyl ether (DME) and Fischer-Tropsch diesel) for two types of vessels (RoPax ferry and large container ship). The study assess environmental impacts generated over the life cycle of the different fuels, from the extraction of resources, fuel production and distribution, and the combustion. By using 18 environmental midpoint indicators, the fuel choices have been compared with respect to their environmental performance. The report emphasized the impact indicators Agricultural land occupation potential (ALO), Global warming potential (GWP) and Particulate matter formation potential (PMFP).

The results give an ambiguous answer of which fuel has the best environmental performance when used for marine applications. The results for LNG show a drastic reduction in PMFP, but the use of LNG does not change the GWP significantly compared to HFO. In addition, the results show that low sulfur fuels in general provide a clear reduction of PMFP. The potential impact of particulate matter is in large extent caused by the combustion process for all fuel choices. The PMFP generated by biofuels is mainly a result of NO_X emissions, while PM and SO_X emissions are also important contributors considering conventional fuels.

In terms of GWP, the implementation of biofuels shows a clear reduction potential. A substitution of HFO with methanol, DME or FT-diesel results in a reduction of GWP equal to 56%, 80% and 78%. However, the results are found very sensitive to inclusion of emissions related to biomass storage. For fossil fuels, the CO_2 emitted along the life cycle is the main contributor of the GWP, while the GWP of biofuels is to a large extent generated by N_2O and CH_4 in addition to CO_2.

Increased agricultural land occupation is a consequence of using biofuels. The performed study shows that the environmental impact is to primarily related to the type of feedstock applied in the biofuel production. The results show lower impact for the fuels produced from short-rotation wood, i.e. Dimethyl ether and FT-diesel, compared to forest wood, which was utilized in the methanol production.

It is believed that this study provide further insight of which processes and stressors are primarily causing potential impacts to the environment along the life cycle of each fuel. Considering the three impact categories emphasized in this study, Fisher Tropsch-diesel and Dimethyl Ether appear as the most promising fuel alternatives for marine application.

Abstrakt

Bruk av skipping utgjør i dag ryggraden til den globale økonomien ved å transportere 80% av det totale volumet av varer i verden. Den globale flåten består av flere typer fartøy, som utfører ulike former for tjenester. Vekst i den globale økonomien fører til en økning av den globale flåten. Dette har ført til økende bekymring, i både lokale og internasjonale miljøer, for miljøkonsekvensene av skipping.

I likhet med andre deler av transportsektoren, er innføring av alternative drivstoffer vurdert som et tiltak for å oppnå en mer miljøvennlig skippingindustri. Formålet med denne studien har vært å utvikle og illustrere en livssyklusbasert tilnærming til vurdering av miljøpåvirkningen av valg av drivstoff for ulike typer fartøy med hensyn til deres driftsmønster.

Livssyklusanalysen utført vurderer bruk av seks ulike drivstoff (tung fyringsolje, marine diesel olje/marin gassolje, flytende naturgass, metanol, dimetyleter og Fischer-Tropsch-diesel) for to typer skip (RoPax ferje og containerskip). Studien inkluderer miljøpåvirkningen av livsløpet til de ulike drivstoffene, fra dyrkingen/uthentingen av råmatrialene, produksjon og distribusjon av drivstoffet til selve forbrenningen. Ved bruk av 18 ulike miljøindikatorer, har det vært mulig å vurdere de ulike drivstoffene opp mot hverandre med hensyn på ulike miljølaspekter. I rapporten er det lagt vekt på miljøindikatorene forbruk av landbruksareal, klimaforandring og partikel formasjon.

Resultatene gir ikke et entydlig svar på hvilket drivstoff som er best egnet for skipping ut fra et miljøperspektiv. Resultatene for LNG viser en drastisk reduksjon i potensiell formasjon av partikler, men bruken av LNG fører ikke til en nevneverdig endring av potensiell global oppvarming. I tillegg viser resultatene en klar reduksjon av potensiell partikler formasjon ved bruk av drivstoff med lavt svovelinnhold generelt. Potensialet for partikkeldannelse er i stor grad forårsaket av forbrenningen av de ulike drivstoffene. For de alternative drivstoffene, LNG og biodrivstoff, er det i hovedsak NO_X utslipp som forårsaker partikkelformasjon, mens også SO_X og direkte utslipp av partikler er viktige kilder med hensyn på konvensjonelle drivstoff.

Resultatene viser et tydelig reduksjonspotensial med hensyn til global oppvarming ved innføring av biodrivstoff når karbonutslipp fra biomasse anses som klimanøtralt. Bruken av metanol resulterte i en reduksjon i globaltoppvarmingspotensiale på ca 56%, mens reduksjonen tisvarte rundt 80% og 78% for innføring av dimetyleter og Fischer-Tropsch-diesel. Studien viser derimot at resultatene er svært sensitive på inkludering av utslipp knyttet til lagring av biomasse. For fossile brensler er utslipp av CO_2 i løpet av livssyklusen hovedårsaken til det globale oppvarmingspotensialet, mens det i stor grad også skyldes utslipp av N_2O og CH_4 ved bruk av biodrivstoff.

Bruk av biodrivstoff fører til et økende beslag av landsbruksarealer. Studien viser at miljøpåvirkningen knyttet til dette er svært avhenging av råmassen som tas i bruk. Resultatene viser at bruk av biomasse med kort rotasjonstid, hvilket ble brukt i produksjonen av dimetylether og Fischer-Tropsch diesel, gir et mye lavere påvirkningspotensiale sammenlignet med bruk av trevirke fra skog, som ble brukt i metanolproduksjonen.

Studien har gitt videre innsikt i hvilke prossesser, utslipp og ressursforbruk som primårt forårsaker miljøkonsekvenser langs livsløpet for the ulike drivstoffene. Med hensyn til de tre miljøindikatorene vektlagt i studien, fremstår dimetyleter og Fischer-Tropsch-diesel som de lest lovende marine drivstoff-alternativene.

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LIST OF ABBREVIATIONS

A	Admiralty coefficient
AP	Acidification potential
BOG	Boil-off-gas
BSFC	Brake specific fuel consumption
BTL	Biomass-to-liquid
CH_4	Methane
CHP	Combined heat and power
CO	Carbon monoxide
CO_2	Carbon dioxide
COS	Carbonyl sulfide
DME	dimethyl ether
ECA	Emission Control Area
EDP	Ecosystem damage potential
EEDI	Energy Efficiency Design Index
EF	Emission factor
EIO	Environmental Input and Output Analysis
EP	Ecotoxicity potential
EPA	Environmental Protection Agency
ETS	Emissions trading scheme
EU	European Union
FT	Fischer-Tropsch
GHG	Greenhouse gas
GTL	Gas to liquid
GWP	Global warming potential
H_2S	Hydrogen sulfide
HCl	Hydrochloric acid
HCLA	Hybrid-Life Cycle Assessment

HCN	Hydrogen cyanide
HFO	Heavy fuel oil
HTP	Human toxicity potential
IMO	International Maritime Organization
IO	Input and Output
ISO	International Organization for Standardization
LBG	Liquefied biogas
LCA	Life cycle assessment
LCI	Life cycle inventory
LNG	Liquefied natural gas
MDO	Marine diesel oil
METS	Maritime Emissions Trading Scheme
MGO	Marine gas oil
NH_3	Ammonia
NMVOC	Non-methane volatile organic compounds
NO_X	Nitrogen oxides
ODS	Ozone-depleting substances
PM	Particulate matter
RME	Rapeseed methyl ester
RO	Residual oil
rpm	Revolutions per minute
SEEMP	Ship Energy Efficiency Management Plan
SMR	Steam reforming
SO_X	Sulfur oxides
SPA	Structural path analysis
SSD	Slow speed diesel
TEU	Twenty-foot equivalent unit
TSE	Taylor Series Expansion
TTP	Tank-to-propeller
USD	United States dollar
VOC	Voltive organic compounds
VOC	Voltive organic compounds
WGS	Water gas shift
WTP	Well-to-propeller
WTT	Well-to-tank

1

INTRODUCTORY CHAPTER

1.1 INTRODUCTION

Shipping has an essential role in the global economy, carrying more than 80% of the total volume and 70% of the total value of transported goods in the world, Asariotis et al. (2012). Vessels can be categorized in multiple segments, e.g. cargo ships, ferries, cruise ships and fishing vessels.

With the growing concern of global warming, air pollution and the impact on human health, attention has been brought to the marine transportation sector, as their emissions are non-negligible on international and regional scale.

The CO_2 emissions from shipping was in 2007 estimated to be 1,046 million tonnes, equal to 3.3% of the global emissions, Buhaug et al. (2009). Research carried out for the International Maritime Organization (IMO), state that these emissions are expected to increase by a factor of 2 to 3 by 2050 if no measures are implemented, Buhaug et al. (2009).

Up to now, heavy fuel oil (HFO) has been the primarily applied fuel in the marine sector. Introduction of international emission regulations like the revised MARPOL 73/78 Annex VI and emission control areas (ECA), imposed by the IMO, are now opening up to alternative fuels in shipping.

To understand the full environmental impact of alternative fuels to the marine fleet, the resource use and emissions along the entire life cycle chain of the fuel must be included in the environmental assessment. This study will use Life Cycle Assessment (LCA) as a tool to assess the potential environmental impact associated with alternative fuels for marine vessels. The report will study the life cycle impacts of the following fuels; heavy fuel oil (HFO), marine diesel oil/marine gas oil (MDO/MGO), liquefied natural gas (LNG), methanol, dimethyl ether (DME) and Fischer-Tropsch diesel.

1.2 OBJECTIVE

The goal of the study is to give an understanding of the environmental impacts and benefits related to various fuel choices for marine vessels. The aim is to develop and illustrate a life-cycle based approach to evaluate the multiple environmental impacts and the sensitivity to fuel choice, operational variables, engine efficiency, etc. for the specific vessels. It is the author's belief that the study will be useful to politicians and decision makers for making trade-offs decisions towards a more sustainable and environmental friendly marine sector.

The study will discuss the following research questions:

1. What are the environmental impacts considered important for ships, and pertinent policies and regulations?
2. What are the findings of the current literature on the life-cycle impacts and climate effects of ships? What is the contribution of different life cycle stages?
3. How can less-important life cycle stages be included in a similar manner in order to simplify the assessment of different ship types?
4. How can knowledge on energy efficiency and combustion-related emissions of ship motors, dependent on operations, the type of ship and engine, and the fuel, be included in the assessment?
5. Is there a trade-off between multiple environmental impacts? What are the factors that might influence the preferred fuel for vessels?
6. What are the most promising low-carbon fuel alternatives for marine application?

The research questions will be discussed during the course of the report, while the key findings will be presented in the concluding chapter.

1.3 SCOPE DEFINITION

1.3.1 TECHNICAL SCOPE COVERAGE

To demonstrate how knowledge on energy efficiency and combustion-related emissions of ship motors, dependent on operational patterns, the type of engine and fuel, can be included in the assessment, representatives from two ship segments have been included in the Life Cycle Assessment. The two types of vessels represent main emission sources among the fleet, with different operational patterns, size and functionality.

The two vessels analyzed in this study are a 4,500 TEU[1] container ship, and a RoPax ferry. The vessels' typical operational patterns will be used in the analysis to assess the environmental performance of each fuel alternative.

Container ships are, as a segment of the fleet, the largest emitter of CO_2 emissions. The segment is emitting 231.53 million tonnes CO_2 per year, based on 2007 numbers by Buhaug et al. (2009). Spread over 4,264 container ships, the emissions are equal to 22% of the total emissions from the world fleet (excluding military and fishing vessels).

RoPax ferries are another important ship segment in terms of emissions. The related CO_2 emission in 2007 were estimated to 60.15 million tonnes, making it the sixth largest emitter among the 15 segments analyzed by Buhaug et al. (2009)

The report will study the life cycle impacts of the following fuel routes:

- Heavy fuel oil (HFO), European production mix from regional storage.
- Marine diesel oil (MDO), European production mix from regional storage.

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[1] The twenty-foot equivalent unit (TEU) is an inexact unit of cargo capacity often used to describe the capacity of container ships and container terminals

- Liquefied natural gas (LNG), from the Barents Sea.
- Methanol, produced from gasification of wood, logging residues and process residues from sawmills.
- Dimethyl ether (DME), produced from gasification of black liquor from a kraft pulp mill.
- Fischer-Tropsch diesel, produced from gasification of short-rotation wood.

1.3.2 TEMPORAL AND GEOGRAPHICAL COVERAGE

Due to the high uncertainty considering the technological development within the transporting fuel industry, the time reference is set to after 2012 and prior to 2015. This have two major effects considering emission factors used in the study:

- It is assumed that the ships are constructed on or after 1st of January 2011, meaning that the vessels are subjected to *Tier II* emission regulations.
- The emission factors will respond to the Annex VI regulations for SO_2, PM, and NO_X set for *on and after 1st January 2012*.

The container ship used in this study sails from East Asia to Europe 6 times a year. The distance covered is about 8,500 NM in each direction. All ships that operate within Emission Control Areas (ECA), defined by IMO, are obliged to meet the emission limits, but what happens today is that international container ships swap the dirty fuels with cleaner fuels only in the ECA, due to the fuel costs, Chryssiakis (2013). The container ship operates in a non-ECA, and it is therefore assumed that the ship will not accommodate the ECA regulations.

The RoPax operates in a limited geographical area, making 20 trips a day. For each trip, the ferry spends 45 minutes on transit and 15 minutes in port. In this study, the geographical scope of the RoPax ferry is set to the Baltic Sea, which are subjected to the ECA regulations. Further information about regulation of emissions from shipping is given in Section 2.3.

The production routes considered is found to be representative in terms of location and technology used. The choice of extraction and production route is also decided, based on data accessibility. The study aims at using reliable and updated data from specific fuel plants, instead of generalized and regional based data. Current production volumes have not been set as a limiting factor. In order to focus on the alternative marine fuels, the current fuels, HFO and MDO/MGO, will be modeled using regional impact data provided by the Ecoinvent 2.2 database.

The production sites modeled in the base-case assessments represents the production processes at the time the data was collected. There has been made no assumption of how the plants have changed their operation since, or how they may evolve in the future. Some of the plants regarded are world-class facilities in term of energy efficiency, while some are still in the research and development-phase, applying the latest technology available.

The following production sites have been used in the life cycle inventory:

- LNG: The liquefaction plant at Melkøya, Norway. The natural gas is extracted from the gas fields Snøhvit, Albatross and Askeladden
- Methanol: The forestry operation, extraction and processing of wood is located to Middle-Norway
- DME: The black liquor gasification plant is located at Örnsköldsvik, Sweden
- Fischer-Tropsch diesel: The biorefinery is located at Örnsköldsvik, Sweden

In terms of deriving the environmental impact potential of the fuel alternatives applied to the vessels, the pollutants' effect on the environment over a time horizon of 100 years have been assessed, following the ReCiPe hierarchist impact assessment model.

1.3.3 FUNCTIONAL UNIT

To be able to compare the different systems as functionally equivalent systems, a functional unit is determined. All process flows in the systems relate to this functional unit.

Out from the study‘s goal, i.e. analyzing the origins of environmental impacts generated by unique marine vessels, using different marine fuels, the functional unit is set to *one year of operation*. The purpose of the functional unit is to perform a comparison of the environmental performance of a vessel, given a yearly operational profile, its engine characteristics and fuel choice.

This LCA will assess the environmental impact over a cradle-to-grave perspective, meaning that the impacts from extraction, production, distribution and combustion of the fuel will be assessed. Due to the objective of comparing alternative fuels, the construction, maintenance and demolition of the ship have been excluded. The included processes make up the system, which delivers the functional unit. Each flow is bounded to the demand imposed to the system by the functional unit.

The assessed fuel life cycle can be illustrated by the following flow diagram in Figure 1.3.3. The dotted line marks the system boundary. The foreground processes are represented in blue boxes, while the economic flows are represented as arrows, indicating the output from the different processes. The methodology of LCA will be further presented in Chapter 4.

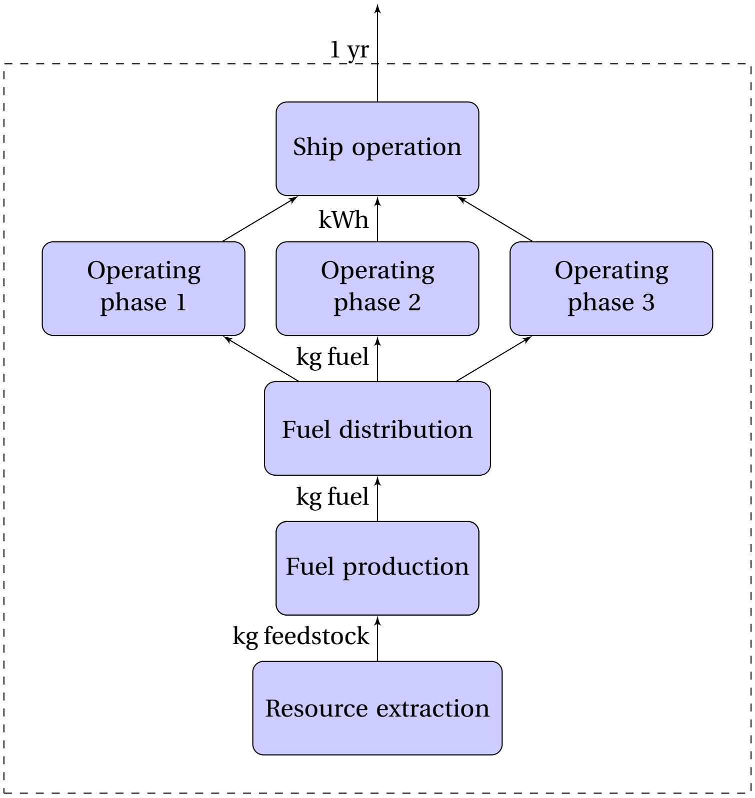

Figure 1.3.1: Flow diagram, marine fuel life cycle

It must be clear though, that the two case studies performed in this study are not directly comparable because of the difference in the service delivered by the system, i.e. the work carried out by a container ship within a year can not be compared by the service delivered by the RoPax ferry since the vessels have two completely different purposes and thus different operational patterns.

1.4 STRUCTURE OF THE REPORT

The report includes 8 chapters and one appendix. A supporting digital appendix is included with the report and is referred to as Appendix D.

Chapter 2 will present the scientific background of the study, justifying the objective of the study and present the different marine fuels that will be assessed in this study. The chapter will summarize the pertinent policies and regulations of the marine sector, and scenarios for future environmental impacts of shipping.

Key findings from the current literature on the life cycle impacts and climate effects of ships will be presented in Chapter 3. In addition to LCA studies, the chapter will present studies on engine combustion of alternative marine fuels.

Chapter 4 will describe the methodology applied for this study. A theoretical overview of LCA will be presented together with limitations and challenges related to the choice of method. The chapter will demonstrate how LCA can be applied for the marine sector to assess the environmental impacts of fuel choices. Use of data tools and key assumptions will be presented and discussed.

The systems analyzed in the LCA will be defined in the Life Cycle Inventory (LCI) in Chapter 5, where the inputs and outputs of the system associated with the functional unit will be quantified. The analyzed systems are defined in the LCI by setting system boundaries and designing of flow diagrams.

In the Life Cycle Impact Assessment (LCIA) chapter the results from the inventory analysis will be processed and presented. The results are presented by 18 impact categories, representing an indicator of a certain form of environmental impact, e.g. climate change, in accordance with the ReCiPe 2008 impact assessment method. Key findings from the Contribution Analysis will also be presented.

The results will be further interpreted and discussed in the in Chapter 7. Sensitivity analysis is performed to assess how dependent the results are on different parameters from the inventory analysis. Issues such as data uncertainty and limitations of the study will be addresses, together with an evaluation of the study conducted and recommendations for future research.

Conclusions from the study will be given in Chapter 8. Key findings and results obtained from the study will be presented in relation to the six research questions considered throughout the report.

In this report HFO and MDO/MGO will be referred to as *conventional fuels*, while LNG, methanol, DME and FT-diesel will be referred to as *alternative fuels*. The six fuels will together constitute the *fuel alternatives*.

2

SCIENTIFIC BACKGROUND

2.1 INTRODUCTION

In this chapter the scientific background for this study will be presented. The two first sections will summarize the emission scenarios published for the maritime sector and the development within regulation of emissions globally and in Europe, respectively. Section 2.4 presents the CO_2 emission distribution, broken down in 15 segments of the fleet. Different emission abatement options and their potential are summarized in Section 2.5.

Section 2.6 is devoted to biofuels to present important aspects of biofuels, such as current production levels, political stance, environmental impact and technical challenges. The section will present different feedstocks used in biofuel production, and which biofuels can be applied to marine vessels. The extended background information provided for biofuels is related to the fact that biofuels are currently applied to ships on a research and development basis.

Section 2.7 will briefly describe the current used fuels, i.e. HFO and MDO/MGO. The fuel alternatives assessed in the study, i.e. LNG, methanol, DME and FT-diesel, will be presented more in detail by its production routes, technological challenges and advantages, and environmental performance. The fossil fuels currently being used by the marine sector will not be described in detail, as they will only be used as a reference in the LCIA. A summary of the characteristics of the fuels will be presented in Table 2.7.1.

2.2 ENVIRONMENTAL IMPACTS OF SHIPPING

Shipping is the most CO_2 efficient way of transporting goods, comparing most modes of transportation, Buhaug et al. (2009). The total amount of goods transported over seas reached 8.7 billion tones in 2012, which equal more than 70% of the total value of transported goods in the world, Asariotis et al. (2012). This makes not only the shipping industry a part of the backbone of international trade, but also a major emitter of GHG and air pollution. The awareness of the associated impacts on the environment, human health and the climate has resulted in a global effort to reduce the environmental footprint of shipping.

A number of the studies that have been published, address the marine sector as significant source of air pollution, Buhaug et al. (2009), Cofala et al. (2007), Eyring et al. (2009), Corbett et al. (2007), Collins et al. (2009). The emitted pollutants are related to environmental problems such as:

- human health effects, e.g. heart and lung disorders
- climate change, i.e. global warming
- ecological effects, e.g. acidification of ocean and rivers

The CO_2 emissions from international shipping[1] was in 2007 estimated to be 1,046 million tonnes, equal to 3.3% of the global emissions, Buhaug et al. (2009). CO_2 is found to be by far the most important greenhouse gas (GHG), both in terms of quantity and of global warming potential (GWP). The total global GHG emissions and its weighted impact are presented in Table 2.2.1.

Table 2.2.1: Summary of GHG emissions from shipping during 2007, Buhaug et al. (2009)

GHG	International shipping	Total shipping	
	[million tonnes]	[million tonnes]	[CO_2 equivalent]
CO_2	870	1050	1050
CH_4	Not determined	0.24	6
N_2O	0.02	0.03	9
HFC	Not determined	0.0004	≤6

Combustion of the conventional marine fuels, i.e. HFO and MGO/MDO, results in air pollution of nitrogen oxides (NO_X), non-methane volatile organic compounds (NMVOC), carbon monoxide (CO), particulate matter (PM), and sulfur oxides (SO_X), in addition to the greenhouse gases. Even though CO and nitrogen oxides (NO and NO_2) have no direct effect on the greenhouse effect, their chemical reactions in the atmosphere may affect the concentration of other GHG in the atmosphere. This leads to indirect greenhouse gas effects. CO does for example form CO_2 in the atmosphere, while emissions of NO_X result in a small reduction of the concentration of methane (CH_4). These indirect effects are however regarded as much less important compared to the emitting of CO_2 and methane, Sir Houghton (2009). Being a resistant compound in the atmosphere, the CO_2 emitted from shipping, will in the longer term cause a positive radiative forcing[2], which is much higher than any shorter-term cooling effects, Buhaug et al. (2009).

Particulate matter, also referred to as aerosols, effect the energy balance as they absorb radiation from the sun and deflect it back to space. The effect of this can be seen in industrial and densely populated areas as the sky seems hazy, though there is no sun present. When sulfur-containing fuels are burnt, SO_2 is emitted, which in turn forms sulfate particulates, which are the most important type of particles in the atmosphere, Sir Houghton (2009). Sulfate particles generate a negative radiative forcing, i.e. greenhouse effect. However, these particles are only present in the atmosphere for a few number of days at the time, imposing short-term environmental impacts mainly to the surrounding region of the emitting source. About 70% of all ship emissions are released with 400 km off the coast, Corbett et al. (1999).

Emissions from shipping impose a risk to human health and ecosystems, primarily in harbor cities, where shipping emissions can be the dominant source of urban pollution, Cofala et al. (2007). Pollutants released through combustion at sea may also be transported in the atmosphere over several hundreds of kilometers, Eyring et al. (2009). Sulfuric compounds cause acid rain, killing insect and aquatic life forms as well as causing damage to buildings. NO_X may increase the concentration of nitrogen in the soil, disturbing the natural balance of the ecosystem. This may for example cause violent growth of algae in rivers and lakes.

Many scientific studies have identified a relationship between elevated levels of fine particles and increased illness and premature death from heart and lung disorders, such as asthma and bronchitis, EPA (2012). Research has also been made on how scenarios for SO_2 and NO_X emissions from shipping affect life expectancy[3], Cofala et al. (2007). A study by Corbett et al. (2007) indicate that shipping-related PM emissions are responsible for approximately 60,000 cardiopulmonary and lung cancer deaths annually world wide.

Shipping increased sulfate particulates, and sulfate and nitrate deposition over Europe in average about 15% in 2010, Collins et al. (2009). In many coastal areas of Europe, it has been estimated that ships will be responsible for more

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[1] *International shipping* has been defined in accordance with the IPCC Guidelines, i.e. shipping between ports of different countries irrespective of vessel's flag. International shipping excludes military and fishing vessels.

[2] Radiative forcing is defined as the difference between radiant energy received by the earth and energy radiated back to space. A positive forcing (more incoming energy) warms the system, while negative forcing (more outgoing energy) cools it.

[3] *Life expectancy* is the average number of years a person can expect to live, if in the future they experience the current age-specific mortality rates in the population.

than 50 percent of sulfur deposition in 2020, Cofala et al. (2007).

Numbers for 2000 states that shipping emitted three times more SO_2 than road traffic, Righi et al. (2011). The SO_2 are high due to the high sulfur content of HFO. NO_X emissions from international shipping increased from 16 million tonnes in 2000 to 20 million tonnes in 2007, Buhaug et al. (2009). The relative high NO_X emissions from shipping can be explained by the high temperatures and pressures most marine engines operate with, and the lack of implementation of effective reduction technologies, Eyring et al. (2009).

As the world economy grows, so does the merchant trade and the need for transportation. The growth the shipping fleet has experienced the past years, has mainly been a result of increased large container and dry bulk transportation. Buhaug et al. (2009) finds the demand for transportation to be the most important variable affecting the growth in future CO_2 emissions. The report stated that very low growth of the fleet, combined with high transport efficiency might reduce the emissions in the future. A transition to low-carbon fuel in the shipping sector is however not expected to be realized in the foreseeable future, Buhaug et al. (2009), Eide et al. (2011), Hektor (2010).

By highlighting the environmental impacts of shipping, pressure has been made on the authorities to enact regulations to the marine sector. The following section will present the current international laws and regulations.

2.3 REGULATING EMISSIONS FROM SHIPPING

The marine sector is regulated by international laws and regulations, and by the current laws and regulations of the nation in which the ship is registered, i.e. the flag State. Ships also have to abide the regulations of the ports and waters they enter.

IMO – the International Maritime Organization – is a United Nation agency responsible for improving maritime safety and preventing pollution from ships. IMO regularly enacts regulations which are broadly enforced by the current 170 member states and three associate members. MARPOL 73/78 Annex VI *Regulations for the prevention of Air Pollution from ships* entered into force in May 2005, and regulate the emissions from international merchant ships. The regulations includes among others NO_X and SO_X emissions and the fuel oil quality.

Limits for emissions of SO_2, particulate matter (PM) and NO_X, are set by geographical location of the operating ships. Table 2.3.1 presents the current and future sulfur limits regulated by IMO, Buhaug et al. (2009). The Emission Control Areas (ECA) and the related regulations are defined in the Marpol Annex VI.

Table 2.3.1: Fuel oil sulfur limits

Outside an ECA	Inside an ECA
4.50% m/m prior to 1 January 2010	1.50% m/m prior to 1 July 2010
3.50% m/m on and after 1 January 2012	1.00% m/m on and after 1 July 2012
0.50% m/m on and after 1 January 2020[4]	0.10% m/m on and after 1 January 2015

The Tier I-III NO_X emission limits are amendments to the Marpol Annex VI. It sets the NO_X emission limits of diesel engines installed (>130 kW) based on the time of ship construction. The emission limits to the respective time horizon are given in Table 2.3.2. The emission limits are not absolute, but sets the limit for the weighted emission average of the engine. Emission factors on high engine loads (>50%) outweigh the emission factors at low engine loads (<50%).

It is expected that the adopted and planned emissions limits will accelerate the development and implementation of abatement technologies, e.g. scrubbers, and improve future prospects for alternative fuels. The expected emission reductions followed by the revised Annex VI are presented in Table 2.3.3, Buhaug et al. (2009).

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[4] depending on the outcome of a review, to be concluded in 2018, as to the availability of the required fuel oil, this date could be deferred to 1 January 2025.

Table 2.3.2: Tier I-III NO_X emission limits for marine engines

Regulation	Time horizon	NO_X limit	Rated engine speeds (revolutions per minute)
Tier I	Ship constructed on or after 1 January 2010	$45 \times n^{-0.2}$ g/kWh	$130 \leq n < 2000$
Tier II	Ship constructed on or after 1 January 2011	$44 \times n^{-0.23}$ g/kWh	$130 \leq n < 2000$
Tier III	Ship constructed on or after 1 January 2016	$9 \times n^{-0.2}$ g/kWh	$130 \leq n < 2000$

Table 2.3.3: Maximum reductions in emissions in the revised Annex VI

	Global	ECA
NO_X (g/kWh)	15-20%	80%
SO_X (g/kWh)	80%	96%
PM (mass) (g/kWh)	73%	83%

The EU has extended the regulations from MARPOL Annex VI with their own Directive 2005/33/EC to limit the sulfur content to 0.1% for harbor regions in 2010. The EU is currently planning to introduce new shipping regulations in 2013 to reduce the emissions, Chestney (2012).

The international effort to reduce emissions of ozone-depleting substances (ODS), has resulted in several international agreements, including MARPOL Annex VI. Significant reductions of CFC and HCFC emissions from shipping have been achieved. The emissions of HFC have however increased, as a result of using HFC as a substitute for CFC and HCFC, Buhaug et al. (2009).

Even though multiple emission regulations have been passed the past decade, international shipping is still excluded from global emission targets, i.e. the Kyoto protocol, and greenhouse gases are still not directly targeted by the enforced maritime regulations. The IMO has presented a number of policies to reduce GHG emissions from the marine sector, which they find conceivable and relevant to the current IMO debate of environmental measures, Buhaug et al. (2009). Some of the options are already enacted, while some still remain as future policy proposals.

One market-based instrument proposed for regulating maritime GHG emissions is a Maritime Emissions Trading Scheme (METS). This scheme can briefly be described as a *Cap and trade system*, which set a cap on the total allowed emission permits, followed by an auctioning of emission allowances/permits. The price of emission permits will be set by the demand and supply. Polluters with high abatement cost will prefer to buy allowances from polluters with lower abatement cost. Cap and trade leads therefore to cost efficiency, where the marginal cost level will be the same for all parties in the market, and set the price of the permit. Such a system will in theory provide strong incentives to invest in abatement technology.

The challenge is to set the right cap, enforcement of emission permits and administration of the scheme. Emission trading schemes have been implemented for SO_2 in the US through the *Acid Rain Program*, and for CO_2 emissions through the EU's ETS, which was the first cap-and-trade system for CO_2 emissions in the world starting in 2005, Ellerman and Joskow (2008). Each ETS has experienced varying level of success, and has not incorporated maritime emissions.

The design of a METS is presented in several submissions to IMO. Based on these, the IMO has presented design features of a METS, which would cover emissions of CO_2 from all ships above a certain size threshold, though with possibilities for modifications. One key feature of the METS is that it would be open for trade with other emissions trading schemes.

Two amendments to the regulations that has been added are the mandatory Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships, which entered into force 1st of January 2013. The EEDI expresses the emission of CO_2 from a ship under specified conditions (e.g., engine load, draught, wind, waves, etc.) in relation to a nominal transport work rate. A mandatory limit on EEDI provides incentives to improve the design efficiency of ships. The main limitation of the EEDI is that it only addresses ship design; operational measures are not considered. The emissions saved through the adaption of EEDI is also limited as the regulation is only applicable to new ships and the potential emission reduction is bound by technical measures. As a management plan, a SEEMP does not require reduction of emissions. It will rather identify cost-effective ways to reduce emissions, Buhaug et al. (2009).

A overview of the identified potential of abatement measures is presented in Section 2.5

2.4 EMISSION DISTRIBUTION ACROSS THE FLEET

In a study performed in 2009 assessed how the emitted CO_2 in 2007 was distributed over the fleet, Buhaug et al. (2009). The world fleet was divided in 15 ship segments, and information of different sub-segments based on size was also studied. The cumulative and absolute values of CO_2 emissions from each ship from each segment are presented in Table 2.4.1.

Table 2.4.1: Contribution to CO_2 emissions: ranking based on emissions per segment

Ship Type	CO_2 Emissions [million tonnes/yr]			Number of Ships			CO_2/Ship [million tonnes/ship-yr]
	Absolut	Cumul.		Absolut	Cumul.		
Container	231.53	231.53	22.0%	4264	4264	4.0%	0.0543
Dry Bulk	173.72	405.25	38.5%	7588	11852	11.2%	0.0229
General Cargo	126.00	531.25	50.5%	20843	32695	30.9%	0.0060
Crude Oil Tank	102.34	633.59	60.2%	2021	34716	32.8%	0.0506
Fishing	72.79	706.38	67.1%	26182	60898	57.5%	0.0028
RoPax	60.25	766.53	72.9%	2819	63717	60.2%	0.0213
Work Boats	53.90	820.43	78.0%	19846	83563	79.0%	0.0027
Product Tankers	47.70	868.13	82.5%	5626	89189	84.3%	0.0085
Chemical Tank.	44.19	912.32	86.7%	3523	92712	87.6%	0.0125
LPG/LNG/Other	37.90	950.22	90.3%	1665	94377	89.2%	0.0228
Vehicle	24.38	974.60	92.6%	711	95088	89.9%	0.0343
Offshore	22.05	996.65	94.7%	5265	100353	94.8%	0.0042
Cruise	20.12	1016.77	96.6%	502	100855	95.3%	0.0401
Passenger	18.73	1035.50	98.4%	3298	104153	98.4%	0.0057
RoRo	16.54	1052.14	100.0%	1669	105822	100.0%	0.0100
Total	1052.1			105.822			

As seen in Table 2.4.1, the carbon intensity is not necessarily high for the largest emitters. Large ships tend to have a higher efficiency rate than smaller ships of same type; e.g. large long-distance ships are usually operating in cruising speed, which increases the efficiency. Still, the long operating distances are causing higher emissions in absolute terms. The absolute CO_2 emissions are especially increasing with size for container ships. On the other side, smaller vessels have a less efficient operating pattern, but they emit less in absolute terms on their covered distance.

2.5 ABATEMENT OPTIONS

To reduce the environmental impacts from shipping, technological and operational measures have been proposed by several scientists. Buhaug et al. (2009) presents in their report for the IMO four *fundamental categories of options for reducing emissions from shipping*:

1. Improving energy efficiency, i.e. doing more useful work with the same energy consumption. This applies to both the design and the operation of ships.

2. Using renewable energy sources, such as the wind and solar power, and second or third generation biofuels.
3. Using fuels with less total fuel-cycle emissions per unit of work done, such as biofuels and natural gas.
4. Using emission-reduction technologies, i.e. achieving reduction of emissions through chemical conversion, capture and storage, and other options.

Eide et al. (2011) showed that the CO_2 emissions can be reduced by 33% from business-as-usual baseline in 2030 at a negative to zero marginal abatement cost, meaning that potential profitable measures for fuel and emission reductions are not fully utilized. Further, Eide et al. (2011) showed that 49% reduction of CO_2 emissions from shipping is achievable for the same scenario with a marginal abatement cost equal to USD 100 per tonne of CO_2 reduced. The modeled abatement options included among others: gas fueled engines, electronic engine control and waste heat recovery.

Buhaug et al. (2009) evaluated the known technical and operational measures in terms of reduction potential of CO_2 per tonne-mile. The result is presented in Table 2.5.1.

Table 2.5.1: Assessment of potential reductions of CO_2 emissions from shipping

Technical and operational measures	Saving of CO_2/tonne-mile
Design (new ships)	
Concept, speed and capability	2% to 50%
Hull and superstructure	2% to 20%
Power and propulsion systems	5% to 15%
Low-carbon fuels	5% to 15%
Renewable energy	1% to 10%
Exhaust gas CO_2 reduction	0%
Operation (all ships)	
Fleet management, logistics and incentives	5% to 50%
Voyage optimization	1% to 10%
Energy management	1% to 10%

As mentioned in Section 2.4, large ships have usually a higher efficiency compared to smaller boats. It is however important that the ships have an efficient operational pattern where the cargo capacity of the ship is fully utilized. Ballast optimization is one way to improve the efficiency of shipping. Replacing the existing fleet with larger vessels have been proposed by Lindstad et al. (2012) as a profitable abatement option with a significant emission reduction potential.There is also an emission reduction potential in increasing the efficiency of cargo handling, berthing and mooring at ports, Buhaug et al. (2009). There are also other means to reduce emission through operational measures, e.g. selection of optimal routes with respect to weather and currents.

Another study presents the emission reductions achievable by varying speed as a function of sea conditions and freight market, Lindstad et al. (2013). The study concluded that lowering speed for shipping will reduce the fuel consumption and thereby the emissions, Lindstad et al. (2011). As a rule of thumb, for all merchant ships, there is a cubic relationship between speed and power (i.e. propulsion power increases in proportion to the cube of vessel speed). Today there is no economic incentive to arrive at the ports just-in-time since the economic compensation of waiting to be loaded/unloaded (demurrage) exceeds the extra fuel cost of increased speed.

This study will analyze the possible environmental benefit from implementing the third option category, i.e. use of biofuels and LNG. Biofuels has until recently not been evaluated for marine applications. The following section will therefore summarize important aspects of biofuels, such as current production levels, political stance, environmental impact and technical challenges. The aim of the extended background information is to give a better understanding of biofuels in general, before the biofuels assessed in this study will be presented together with the other fuel alternatives.

Key findings from previous environmental assessments related to the IMO's third option category and the objective of this report will be further reviewed in Chapter 3.

2.6 BIOFUELS

2.6.1 BIOFUEL PRODUCTION TODAY

Biofuels are liquid or gaseous fuels that can be produced from various forms of organic and cellulosic materials, excluding fossil fuels. In other words; the biofuel must originate from a recent biological material.

It is normal to distinguish the biofuels in generations; *first-generation biofuels* are produced by food crops or oil seed crops, e.g. currently is almost all bioethanol produced from grains, mainly from the US, or sugar crops, essentially from Brazil.

Second-generation biofuels are produced by organic waste material, such as fish waste, marine and animal oil, or by cellulosic materials, e.g. grasses, trees, wood processing, and different types of waste products and residual from crops. Due to the possible environmental impact of first-generation biofuels, presented in Section 2.6.3, this study will solely focus on second-generation biofuels.

Biomass can be converted into transportation fuels by multiple production routes, and the current and prospective feedstocks are diverse. Figure 2.6.1 shows the different conversion routes from biomass to different second-generation biofuels.

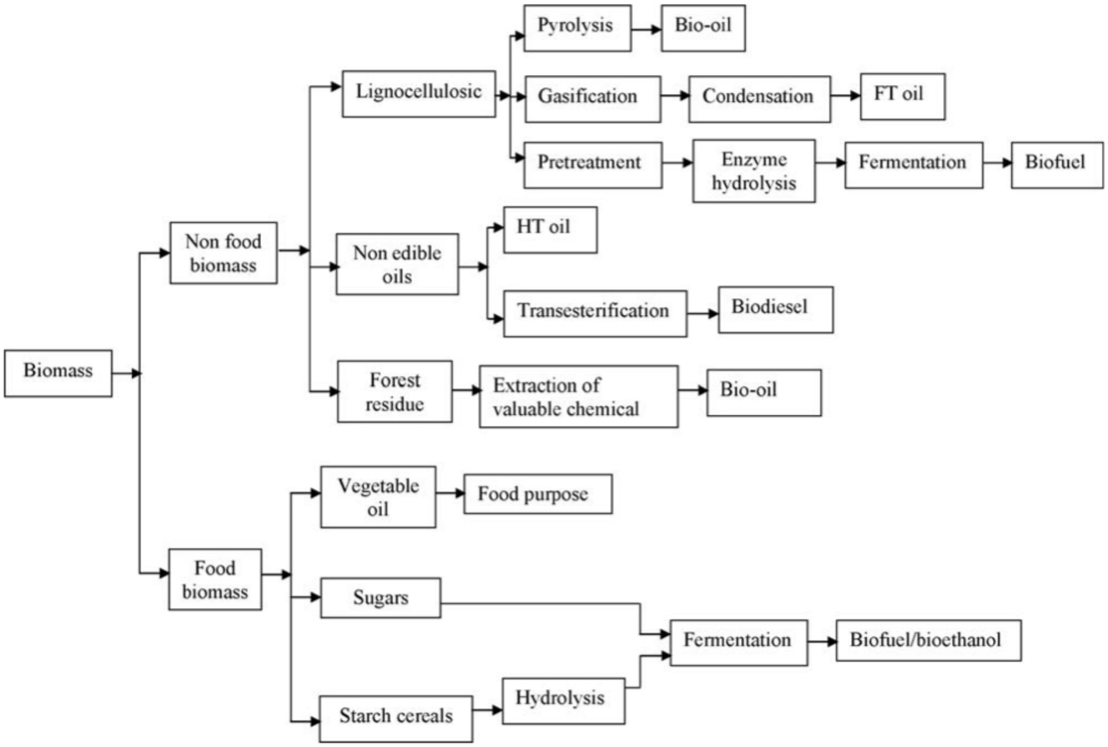

Figure 2.6.1: Second-generation biofuel production from biomass, Naik et al. (2010)

It should be mentioned that there are more types of biofuels being researched. *Third-generation biofuels* are biofuels produced from vegetable oil, derived from algae. The production route is technically feasible, Opdal and Fjell Hojem (2007), but is currently still in a conceptual phase. The advantage of using algae as feedstock for biofuels is the astonishing growth rate and the possibility of cultivation in desert areas and other unproductive sites. *Forth-generation biofuels* are created using petroleum-like hydroprocessing or advanced biochemistry, Kagan (2010) . These two generations of biofuels will not be further referred to in this report.

2.6.2 POLITICAL STANCE

It is believed that the biofuels industry will be heavily influenced by politics in the years to come. Up to now, regulations and legislations as the EU directive on renewable energy (2009/28/EC) and the US Environmental Protection Agency (EPA) Renewable Fuel Standard version 2, have worked as a momentum in the biofuel industry.

There are two main reasons for policymakers to facilitate for the biofuel industry:

- Climate change mitigation
- Secure energy supply

In order to reduce the anthropogenic emissions of GHG, shift in the energy consumption from fossil fuels to biofuels is evaluated in the marine community, Buhaug et al. (2009). Stricter regulations of sulfur contents in the fuel increase the demand of low-sulfur fuels. This has increased the interest in alternative fuels like LNG and biofuels.

The need of reducing the consumption is also closely related to energy supply and so forth national security. As the exporting countries of fossil fuels are experiencing political instability and conflicts, importing countries are now looking for alternatives in order to maintain a secure energy supply. The US have for example invested heavily in shales gas, ethanol and renewables in order to reduce their energy deficit.

2.6.3 ENVIRONMENTAL IMPACTS OF BIOFUELS

Many politicians and scientists have emphasized biofuels as a measure to reduce the global warming, with the argument that CO_2 emissions from biofuels combustion are climate neutral by assuming the biofuel system to be carbon neutral i.e. the amount of carbons emitted by combustion are equal to the amount of carbon taken up by the plants during growth. There are however certain requirements that must be met to call a biofuel completely CO_2-neutral, Alvfors et al. (2010):

- the carbon dioxide emissions to the atmosphere, originating from the biofuel combustion, must be absorbed in growing biomass
- the emissions of non-CO_2 greenhouse gases due to the use of the fuel, must end or be compensated for
- the soil carbon, connected to the biomass production, needs to be constant
- all input energy for agriculture/forestry and fuel production need to be CO_2-neutral

Carbon neutrality is widely adopted in life cycle assessments. To maintain this *carbon balance*, LCA databases, such as Ecoinvent 2.2, biomass is given a CO_2 credit, which is used to offset the carbon content of biogenic air emissions. The carbon balance is maintained by applying the following equation for each unit or multi output process in Ecoinvent, Jungbluth et al. (2007a):

$$C_{\text{in, resource}} + C_{\text{in, pre-products}} = +C_{\text{out, emissions}} + C_{\text{out, process-output}} \tag{2.6.1}$$

Where:

$C_{\text{in, resource}}$ = CO_2 from air

$C_{\text{in, pre-products}}$ = all biogenic carbon content of inputs from processes from technosphere

$C_{\text{out, emissions}}$ = carbon content of biogenic air emissions of CO_2, CH_4, CO, NMVOC and carbon emissions to water

$C_{\text{out, process-output}}$ = carbon content of the process output to technosphere

Some LCA software apply the carbon balance by excluding biogenic CO_2 emissions in the impact calculations. This simplifies the work of maintaining the carbon balance, but eliminates the possibility of manually adjustment of biogenic carbon fluxes.

There are however scientists that are questioning the convention of carbon neutrality of biofuels systems, and believe that the climate impact of bioenergy is underestimated. One argument is that CO_2 emissions from biomass combustion spend time in the atmosphere and contribute to global warming, before it gets sequestered by biomass, Cherubini et al. (2011). The longer biomass rotation period (i.e. the time it takes for the biomass to regrow), the longer is the mean stay of CO_2 in the atmosphere and the climate impact increases. The study by Cherubini et al. (2011) also confirms that *bioenergy is a climate change mitigation strategy particularly effective for long-term targets*.

One way to include the climate change impact of biofuels is to implement characterization factors for biofuels, quantifying the generated global warming from biofuels combustion. The characterization factors will depend on the rotation time of the biomass, and the time horizon evaluated, Cherubini et al. (2011). How characterization factors are used in LCA to determine environmental impacts are further explained in the Methodology chapter, Section 4.2.

The term *life cycle performance* of a product is currently being adopted in the biofuel policies. In countries subjected to Directive 2009/28/EC, life cycle GHGs from a biofuel must be reduced at least 35% compared to fossil fuel in order to be able to count the biofuel as renewable, Commission et al. (2009). Further, a 50% reduction will be required in 2017, while 60% will be the minimum required reduction of GHG emissions in 2018.

Increased production of biofuels grown on agricultural land will affect the price on other agricultural products, such as food. Leveled food prices can be unbearable for urban poor, while it might lead to increased welfare for those who have their income linked to agriculture. Environmental assessments have also shown fluctuating results for first-generation biofuels. The debate of increased food prices and environmental impact has muted much of the enthusiasm around biofuels in general, and the focus has turned to second and third generation biofuels.

2.6.4 CHALLENGES AND LIMITATIONS

High infrastructural costs and technological challenges remain to the use of biofuels. Hektor (2010) mentions the renewal of the car fleet as one important factor that will influence the biofuel industry. Other mentioned factors are: technology funding, sustainability, renewable energy regulations and food versus fuel issues. Technological challenges, i.e. corrosion, permeation and swelling, vary significantly for different biofuels, Sridhar et al. (2010).

The current share of biofuels in shipping is insignificant, and there has been little practical experience with biofuels in the marine sector. Still, the limited numbers of projects using biofuels in ship have demonstrated that most existing engines are compatible with biofuels with modifications. Local emissions of smog and sulfur has been the driving force behind many of these projects. This will not be presented in detail in this study, but is referred to in the literature, Opdal and Fjell Hojem (2007), Florentinus et al. (2012).

Research do show that diesel engines are compatible with biofuels such as biodiesel, vegetable oil, gas-to-liquid (GTL) and Biomass-to-liquid (BTL) without significant modifications, and that Otto engines are able to run on ethanol, methanol, natural gas, LNG, LBG as well as gasoline, Florentinus et al. (2012). Even though blends with biofuels and hydrocarbons are regarded as most applicable, blendings up to 100% biodiesel have been tested, Alvfors et al. (2010), Opdal and Fjell Hojem (2007).

Second-generation biofuels are not expected to be commercially available on large scale before 2015, Hektor (2010). Nor is it believed among stakeholders that biofuels will cover more than 10% of the consumed fuel in the transporting sector on a global level. It is assumed that biofuels will be sold as blends with fossil fuels.

2.7 FUEL CHOICES FOR MARINE VESSELS

2.7.1 HFO/MDO

Heavy fuel oil (HFO) is a high sulfur content fuel, and makes up approximate 80-85% of the total fuel consumption by the global merchant fleet, Chryssakis et al. (2011). HFO is pure or nearly pure residual oil [5]. HFO constitutes 3.8% of the total oil production, in comparison do gasoline and diesel make up 65% of the total.

HFO is not expected to be readily biodegradable, making it an environmental threat in the case of spill events. The high emission rates of pollutants, like CO_2, SO_2 and NO_X, has made governments and institutions to advocate reduction of the HFO consumption.

Marine diesel oil (MDO) and marine gas oil (MGO) are currently covering between 15-20% of the total fuel consumption by the global merchant fleet, Chryssakis et al. (2011). MDO are MGO are blends of gas oil and heavy fuel oil. The fuels have no significant differences in terms of emission factors compared to HFO considering CO_2 and NO_X. The reduced sulfur level does, however, result in lower SO_X-emissions, making the fuels attractive for shipping in ECA.

2.7.2 LNG

Liquefied natural gas (LNG) is natural gas that is cooled down to $-163°C$ at atmospheric pressure and condenses into a liquid fuel. The volume is approximately 600 times less compared to natural gas.

LNG has by several scientists been referred to as the most promising alternative fuel for shipping in the short term perspective, Chryssakis et al. (2011). The expectations of a lower price on natural gas compared to prices for low sulfur fuel-oil, and future accessibility are key factors behind the support. LNG is currently being used as fuel in 38 ships globally, and 30 new ships are confirmed built towards 2015, excluding LNG carriers and inland waterway vessels, Chryssiakis (2013). A LNG fuel system was newly applied for a 3,100 TEU container ship by a South Korean shipyard, DMSE, which states that the installation is a *world first*, Chew (2013). Only a few bunkering sites exists today, mainly located in Norway. However, several large scale LNG terminals are under development in Europe. The total liquefaction capacity in Northern Europe is expected to grow considerably the coming years. From 2011 to 2018, the capacity shall increase from 4.8 million tonnes per year to 13.5 million tonnes, Chryssakis et al. (2011).

LNG has a higher hydrogen-to-carbon ratio compared to HFO and MDO, which equals to a lower carbon intensity (kg CO_2/kg fuel). LNG composite of typically 70-90% methane, 5-15% ethane, while propane and butane make up to 5%, Verbeek et al. (2011). Before the liquefaction, the natural gas is purified by removing CO_2, hydrogen sulfide, mercury, water, oxygen residue and heavier hydrocarbons (C_{5+}). The fuel does not contain sulfur, meaning the SO_2 emissions will be equal to zero and the PM emissions significantly reduced by using LNG as fuel in marine vessels, Buhaug et al. (2009). LNG combustion results in less CO_2 emissions compared to average diesel combustion, but methane leakages may reduce the GHG-gain considerably.

One of the main obstacles of introducing LNG on large scale, is the high infrastructural costs. The study performed by Ryste (2012) concluded that *LNG bunkering requires substantially more preparation and maintenance of the system than for other fuels.*

Even though the storage tanks are designed to keep the LNG at $-163°C$, the tanks cannot be perfectly insulated, and heat exchange with the surroundings will occur. When the surface temperature of the LNG exceeds $-162°C$, the liquefied gas evaporates. The result is called *Boil-off gas* (BOG), and it is generated through all life stages of

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[5] Residual means the material remaining after the more valuable cuts of crude oil have boiled off.

LNG. Norwegian standards states that *BOG that is formed at the plant shall wherever practically possible be recovered and routed to flare or vent*, NS (2007). Known alternatives for BOG handling are however ventilation to air, flaring, electricity generation, and re-liquefaction, Hasan et al. (2009).

Research shows that for voyages over ten days or more, 80% of the BOG is generated during the laden and ballast transit while the remaining BOG is formed during loading and unloading, Hasan et al. (2009). The boil-off rate through the transportation of LNG is affected by several factors; e.g. sea conditions, LNG composition, ambient temperature, overall thermal transmittance of the storage tanks, tank pressure and operating modes, Hasan et al. (2009). The BOG that is formed during the transportation over seas is usually vented out of the storage tank and used as a fuel for propulsion or auxiliary needs.

2.7.3 SYNTHETIC GAS

Biomass-to-Liquid (BTL) is an expression for the process of converting biomass into a synthetic liquid fuel. In this study, the biofuels assessed will be produced from synthetic gas, also referred to as syngas. The syngas comprises carbon monoxide and hydrogen, and is created by heating the biomass to above 700°C in an oxygen poor environment, Jungbluth et al. (2007a). The syngas is a universal intermediate to a broad range of BTL transportation fuels, e.g. gasoline, methanol, ethanol, dimethyl ether, Fischer-Tropsch diesel, etc.

The characteristics of syngas are highly dependent on the technology considered, and the post-gasification treatment steps, which in turn depend very much on the use of the gas downstream of the gasification, Jungbluth et al. (2007a). Nevertheless, the synthetic diesel produced from syngas has very similar properties to petroleum diesel.

Syngas can be derived from a number of different feedstocks, e.g. coal, natural gas, and biofuels, and can be processed into multiple of products for various applications, e.g. synthetic liquid fuels, chemicals and combined heat and power (CHP) production. A selection of options are illustrated in Figure 2.7.1. The products marked in green are the synthetic fuels that will be assessed in this study, and a brief description of each fuel is given in the following sections.

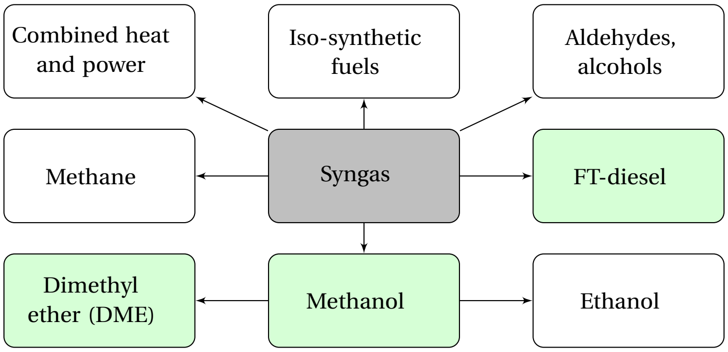

Figure 2.7.1: Schematic diagram of synthetic fuels and chemicals production from syngas

There are two main gasification technologies; fixed bed and fluidized bed gasifiers. Each technology has variations of their own, e.g. direction of air flow, operational temperature and pressure.

In order to utilize syngas in methanol synthesis and Fisher-Tropsch synthesis production, the syngas has to be processed and conditioned. Syngas produced from biomass will in addition to CO and H_2 contain contaminants such as H_2S, HCl, NH_3, HCN, COS, dust and alkalis. Removal of these contaminants from the syngas is necessary before entering the subsequent fuel processing.

The most common method for reforming the syngas is the Steam reforming (SMR) method, which uses steam as the conversion reactant. The synthetic gas produced from the woody biomass contains considerable amount of methane in addition to H_2, CO and CO_2. At the reforming device, methane, ethylene and ethane is reacting with the steam, resulting in carbon monoxide and hydrogen. The reaction is highly endothermic, meaning energy in form of heat must be added in the reaction, which takes place over a suitable catalyst. Typical temperatures range from 850°C to 1000°C. The process can be described by the following chemical reactions:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{2.7.1}$$

$$C_2H_4 + H_2O \rightarrow 2CO + 4H_2 \tag{2.7.2}$$

$$C_2H_6 + H_2O \rightarrow 2CO + 5H_2 \tag{2.7.3}$$

After the reforming, the gas enters a shift-reaction in order to increase the H_2:CO ratio, for a more ideal methanol synthesis. The process is called a water gas shift (WGS), and can be expressed as follows:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \tag{2.7.4}$$

CO_2 may have to be removed from the gas in order to reach the desired (H_2+CO_2):(CO+CO_2)-ratio. CO_2 can be removed through different physical and chemical reactions, but the use of amines is the most conventional and commercial best proven option Jungbluth et al. (2007a). MEA (monoethanolamine) is today the most commonly used amine in CO_2 capture processes, Shao and Stangeland (2009), ZERO (2013). When the gas comes in contact with the amines, the CO_2 adheres to the amines in a weak binding, which is later separated through a regeneration process, using hot steam. The CO_2 can either be stored or emitted, while the amines are reused. The process requires heat and electricity. The heating required to separate CO_2 from the amine solution requires the largest amount of energy, ZERO (2013).

2.7.4 METHANOL AND DME

Methanol is the simplest alcohol, with the chemical formula CH_3OH, and is a light, colorless, flammable liquid at room temperature [6]. Methanol occurs naturally in the environment and can be made from multiple different feedstocks, e.g. natural gas, coal, agricultural waste. Methanol has the lowest carbon content and the highest hydrogen content of any liquid fuel, MetanolInstitute (2013).

Methanol is produced by treating the carbon oxides in the syngas with hydrogen over a catalyst. The catalyst is commonly made of copper oxide, zinc oxide, aluminum oxide or chromium oxide. The chemical reaction is given by the following exothermic reaction:

$$CO + 2H_2 \leftrightarrow CH_3OH \tag{2.7.5}$$

To deal with excessive hydrogen, carbon dioxide is injected in the reactor, to form methanol according to the equation:

$$CO_2 + H_3 \leftrightarrow CH_3OH + H_2O \tag{2.7.6}$$

The water that is produced can be recycled in the WGS process in order to produce hydrogen. The reaction is given by Equation 2.7.4.

The two main technologies for methanol synthesis are *conventional gas phase fixed bed reactors* and *liquid phase reactors*.

Methanol is currently being produced in several countries globally. In 2010, the global consumption of methanol was over 48 million metric tonnes, which is roughly equivalent to global ethanol fuel demand, Chryssakis et al. (2011).

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[6] Methanol is liquid from −93°C to +65°C at atmospheric pressure.

Methanol is generally made from natural gas, Jungbluth et al. (2007a). To production of methanol from biomass, e.g. cellulosic material, is technically feasible, but currently limited to research and development projects.

In the Netherlands, BioMCN produces second-generation bio-methanol by utilizing residue from processing vegetables and animal fats. In Sweden, Chemrec is producing methanol and Dimethyl Ether (DME) from the waste product black liquor[7] from pulp mills.

DME is a non-toxic, colorless gas that condenses into liquid phase at pressure about 0.5 MPa. DME is the simplest form of ether, with the chemical formula CH_3OCH_3. DME can be produced from a variety of carbonaceous feedstocks. The currently leading production route is dehydration of methanol produced from syngas. Alternatively, it can be directly produced by combining the process steps using appropriate catalysts. The dehydration of methanol can be expressed by the following equation:

$$2CH_3OH \rightarrow CH_3OCH_3 + H_2O \tag{2.7.7}$$

DME has similar properties to liquefied petroleum gas (LPG), and can be directly applied to diesel engines. The fuel has the same requirements for handling and storage precautions as LPG. Technical challenges are related to corrosion and low viscosity, Chryssakis et al. (2011). A disadvantage is the low heating value, which would require larger quantities of fuel compared to conventional fuels. DME has, however, a high cetane number (>55) and low critical temperature which yield a short ignition delay, which again results in low NO_X emissions and reduced noise, Chryssiakis (2013).

Historically methanol has, together with ethanol, been used extensively as an automotive-fuel. Stena Line, an international transport and travel service company and one of the world's leading ferry operators, is one company that has faith in methanol as a fuel alternative to conventional fuels. They believe that *"methanol is a more realistic option in the short term than LNG"*, Ramsdal (2013b). The auxiliary engines on one of their ferries, operating between Gothenburg and Fredrikshavn, will run on DME, made by methanol. The goal is that also the main engine will be able to run on DME in the future. The project started in April 2013, and if the tests succeed, Stena Line's vision was that 25 of the company's 34 ferries will be converted to operate on DME from methanol within 2018, Ramsdal (2013b). Stena Line has also modified vessels for direct use of methanol, Chryssiakis (2013). By using DME as a fuel, Stena Line believe they can achieve NO_X reductions that satisfy Tier III NO_X standards, while there is more uncertainty concerning NO_X emissions from methanol, Chryssiakis (2013). It is expected that the cost and emission requirements will be the decisive factors for which fuel will be applied in the future.

2.7.5 FISCHER-TROPSCH DIESEL

Another form of BTL process is Fischer-Tropsch (FT) diesel , after the two scientists that invented the process in Germany in the 1920s.

The biomass is first transformed into syngas (see section 2.7.3) and then converted into liquid hydrocarbon fuels by the FT-process. The FT-process involves a series of chemical reactions that produce a variety of hydrocarbon molecules according to the formula C_nH_{2n+2}. The end product is a biodiesel fuel with energy density comparable to conventional diesel, see Table 2.7.1.

The only requirement for the feedstock used in the FT-process is that the material includes carbon, Adlam (2007). The FT-diesel has for example previously been derived from coal and natural gas.

The biofuel is obtained by using highly selective catalysts, making the sulfur content practically equal to zero, Chryssakis et al. (2011). However, the gasification process may be very energy intensive, and will require CO_2 sequestration systems to be able to compete with conventional fuel production.

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[7] Black liquor is the spent cooking liquor from the kraft process when digesting pulpwood into paper pulp removing lignin, hemicelluloses and other extractives from the wood to free the cellulose fibers.

Since FT-diesel has practically the same composition and properties as diesel, FT-diesel can be applied without additional safety considerations than those for conventional fuels.

The FT-diesel has currently been used for road transportation and as jet aviation fuel. It is possible to use FT diesel in blends with heavier distillates in order to meet the imposed sulfur limits in ECAs, Chryssakis et al. (2011). Rambøll, a Norwegian consulting firm, believe that it will be technical and economical feasible to use FT-diesel, produced by Norwegian wood, for Norwegian airplanes. One prerequisite for the conclusion is that the byproducts from the biodiesel production are marketable, Ramsdal (2013a).

2.7.6 FUEL CHARACTERISTICS

Fuel characteristics for the different fuels are presented in Table 2.7.1. The properties are given in atmospheric conditions, i.e. 25°C and 1 atm. The conventional fuels and LNG characteristics are taken from Chryssakis et al. (2011), while the methanol characteristics are based on the numbers provided by Jungbluth et al. (2007a). The LHV of DME and FT-diesel is taken from Jungbluth et al. (2007b).

Table 2.7.1: Fuel characteristics

Fuel	Lower Heating Value [MJ/kg]	Density [kg/m^3]	Cetane Number	Octane Number	C/H/O [mass %]	Boiling Point °C
HFO/MDO	41.2-42.7	830-985	40-55	-	86/14/10	180-360
LNG	48.6	448.39[8]	-	>120	75/25/10	-162
Methanol	20.0	792	-	110	38/12/50	64
DME	28.4	668	55-60	-	52/13/35	-25
Fischer-Tropsch	43.2	760-790	55-75	-	85/15/0	180-230

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[8] Based on average Norwegian characteristics. Calculated according to ISO 6578 [T = -160°C]. Gas density [kg/m^3] = 0.78, calculated according to ISO 6976[0°C, 1.01325 bar], Robin and Demoury (2012)

3

LITERATURE REVIEW

3.1 INTRODUCTION

This chapter will present the findings of the current literature on the life-cycle impacts and climate effects of ships. The methods used in past environmental assessments of shipping will be presented and discussed, together with key findings.

3.2 METHODS USED IN PAST STUDIES

Many scientists have published work on the environmental impact of shipping the past couple of years, confirming the rising concern of the marine sector's environmental footprint. The studies are varying in scope and goal, while the main focus has been on estimating the CO_2, SO_2 and NO_X emissions related to combustion of conventional marine fuels, i.e HFO and MDO/MGO.

Life cycle assessment (LCA) is a methodological framework for estimating and assessing the environmental impacts, such as global warming potential (GWP), attributable to the life cycle of a product, Rebitzer et al. (2004). Life cycle assessments are often divided into *attributional* and *consequential* LCA. The attributional LCA aims at describing the environmental performance of a life cycle and its sub system, and includes the full life cycle, e.g. construction and demolition of a system. Consequential LCA includes only the processes of the system that will differ between the alternative systems/fuels, and is therefore less resource consuming and often preferred for comparative studies. The methodology of LCA will be fully presented in Chapter 4.

Only few *screening* LCA studies related to shipping have been published. A screening LCA gives an overview of the environmental impacts of a subsystem of the value chain. The intention is often to identify environmental hotspots that previously have not been assessed in studies, and the level of detail makes this type of LCA unsuitable for comparative studies due to the resource intensity.

The recent published consequential LCA of marine fuels are so-called well-to-propeller (WTP) studies, e.g. Bengtsson et al. (2011), Bengtsson et al. (2012), Verbeek et al. (2011) and Chryssakis and Stahl (2012). The studies assess the environmental impact potential of alternative fuel systems across the extraction, production, refining, distribution and combustion of the fuel. The studies often exclude the environmental impact associated with contraction and demolition. The results are often presented in a breakdown of impacts related to processes along the path from the extraction to the fuel tank (well-to-tank), and to the operational-phase (tank to propeller). The main processes and their emissions included over WTP perspective are illustrated in Figure 3.2.1.

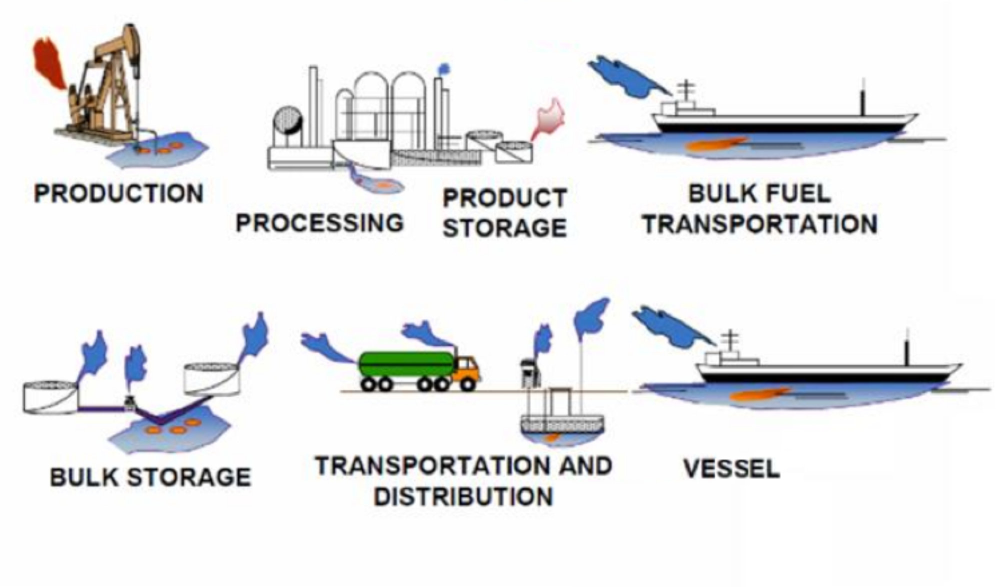

Figure 3.2.1: Key processes of WTP analysis, Chryssakis and Stahl (2012)

A limitation with this breakdown is that it does not show how the specific processes along the life cycle influence the result. The presentation makes a clear distinction between combustion related impacts and production related impact, but limits the learning outcome for the reader. This is especially an issue for environmental assessments of biofuels, where the carbon emissions in the TTP-phase is often set to zero, making the results from each step in the WTT stage even more important for further studies.

A screening LCA has been performed of a Color Line passenger vessel by Johnsen and Fet (1999), including inputs such as hull materials, main machinery and equipment for crew and passengers.

3.3 KEY FINDINGS FROM PREVIOUS LCA STUDIES

The following section will summarize the main finding from the literature describing the environmental impact of fuels applied for marine vessels. Notice should be made to the fact that there are multiple articles available on transport fuels, but this section will solely focus on the studies that has been made of fuels in relation to shipping operations. Key findings from specific studies are presented in Table 3.4.1.

- *Previously studied fuels:* Most of the published consequential LCA studies and other environmental assessments of marine fuels that have been published, focus on oils, distillates and LNG. Only a few environmental assessments on biofuels for shipping have been published. Capital goods and demolition processes are usually excluded.
- *Studies on use of biofuels:* Few environmental assessments on biofuels for shipping have been published. Bengtsson et al. (2012) assess the environmental impacts of substituting HFO with marine gas oil (MGO) and LNG with biofuels on RoPax ferries over a WTP-perspective. The four biofuels analyzed were rapeseed methyl ester (RME), synthetic biodiesel (BTL), liquefied biogas (LBG) and liquefied bio-methane. The LBG was modeled to originate from agricultural waste, manure and municipal organic waste, while the BTL and liquefied bio-methane were modeled to originate from forest residues, making the three fuels a second-generation biofuel. The results did not un-ambiguously state that switching into biofuels will decrease the environmental impact. The GWP was the impact category that was reduced the most by using biofuels, while the eutrophication potential increased in this study. Impact associated with agricultural land use is exclusively linked to production of first-generation biofuels.

- *The contribution of different life cycle stages:* In the consequential study by Corbett and Winebrake (2008), the operational-phase accounted for 86.3%-89.8% of the CO_2 emissions along the life cycle of residual oils, MGO and MDO. The emissions related to extraction, processing and distribution of the fuels accounted for 6.7%-10.2%, excluding capital goods and demolition. The results are only presented by total CO_2 and SO_2 emissions, not in environmental impact categories. Bengtsson et al. (2011) compared HFO, MGO, GTL and LNG, and found that the impact from TTP-phase represents 50-99% of the environmental impact, depending on category and fuel alternative. The screening LCA of a Color Line passenger vessel by Johnsen and Fet (1999), found that for some impact categories, i.e. GWP, Acidification potential (AP), Ecotoxicity potential (EP), Human toxicity potential (HTP), Ecosystem damage potential (EDP), operational-phase is responsible for more than 95% of the impact potential. The impact assessment also showed that construction can be important for some impact categories, i.e. ozone depletion, solid waste and material use. Maintenance is to some extent important for ecotoxicity, material use, ozone depletion and solid waste.
- *Sensitivity factors:* The environmental performance of LNG and other methane based fuels have been found sensitive to methane leakages, which strongly affect the overall GWP, Bengtsson et al. (2011), Bengtsson et al. (2012). Bengtsson et al. (2011) points out the choice of how allocation of byproducts, e.g. energy, affects the overall results, and use an energy-content based allocation. Another sensitive factor is that the electricity mix used will highly affect the overall environmental performance of the fuels, as the liquefaction processes for LBG is a very energy intensive processes, Bengtsson et al. (2012). The study by Corbett and Winebrake (2008) state that *refining efficiencies determine the magnitude of the change in CO_2* considering the life fuel cycle of residual oils (RO), MGO, MDO and associated blends. Bad efficiency rate may even result in a negative tradeoff. The impact from solid waste and material use of the ship can be substantially reduced by scrapping/recycling, Johnsen and Fet (1999).
- *Developed software tools:* Scientists are currently working on a LCA software for ships and Life cycle inventory (LCI) Analysis based on shipbuilding, actual shipbuilding operation, dismantling and recycling activities, Kameyama et al. (2005), Jivén et al. (2004). These types of software come short to compare different alternatives regarding fuels. They rather intend to provide an attributional LCA, focusing on the internal system and materials consumed, in order to document the environmental performance of a ship operating with currently applied fuels.

3.4 LIMITATIONS AND UNCERTAINTIES

Incomplete system boundaries are often the main weakness of a LCA, and may cause biased results. In terms of LCI of biofuels, agricultural processes and forestry operation might be excluded. Storage of biofuels have been proven to generate significant amounts of methane, Bright and Strømman (2009), which can be decisive for the overall GWP of the system.

The LCA of marine fuels by Bengtsson et al. (2012), is one study where it is assumed that the feedstock are based on forest residue and environmental impacts of forestry operation is not allocated to the used residues. The LCA might be transparent and the assumptions well justified, but it is important that policy strategies are based on realistic scenarios and the environmental assessments based on these. Without investigating the inventory data of a LCA article, wrong impressions of a system's environmental performance can be made. The accessibility of supporting information to scientific articles are therefore most important.

As Petzold et al. (2011) said it: *Including all relevant sources of GHG emissions during biogenic fuel production and use is an indispensable prerequisite for an integrated assessment of climate impacts of biogenic fuels.*

It must be noted that there has been carried out several life cycle assessment, or well-to-wheel analysis of biofuels, Bright and Strømman (2009), Jungbluth et al. (2007a), Forsberg (2000). They are however limited to passenger cars or trucks. The studies bring important information about the production chain of biofuels, but due to the high diversity with respect to engine characteristics, the emission factors measured from cars are not directly applicable to marine engines.

Table 3.4.1: Key findings from previous research

Type of study	Fuels analyzed	Indicator/(Pollutants)	Key findings	Reference
Con.LCA	HFO, MGO, GTL, LNG	GWP (CO_2, CH_4, N_2O), AP (NO, NO_2, NO_X, SO_2, NH_3), EP (NO, NO_2, NO_X, NH_3)	HFO the most energy efficient, and most polluting Small differences in GWP. LNG results dependent on CH_4 slip. GTL less favourable than HFO in terms go GWP. The AP is significantly reduced for LNG, and for MGO and GTL with scrubbers.	Bengtsson et al. (2011)
Cons.LCA	HFO, MGO, RME, BTL, LNG, LBG, LB-CH4	GWP, AP, EP and PM10	AP and sulfur content highest for HFO. TTP-phase dominate the AP for all fuels, except for BTL and RME. EP lowest for the fossil fuels, largest for BTL and RME. WTT-phase has significantly higher contribution. PM10 lowest for gas based fuels (i.e. LNG and LBG). Fossil fuels are contributing the most to global warming. BTL, LBG, and LB-CH4 had the least GWP. No significant difference in overall environmental performance of MGO and LNG.	Bengtsson et al. (2012)
TEAMS (total fuel cycle analysis)	RO, MGO, MDO, and associated blends	CO_2, SO_2	Compared to RO, MGO and MDO reduce the life cycle SO_2 emissions reduced by 70-80% compared to RO In terms of CO_2, the refining efficiencies and fuel densities are determent. The fuels showed no or little change in CO_2 ranging from 0.16-0.47% compared to IFO 380	Corbett and Winebrake (2008)
Environmental Assessment (WTP)	LNG, HFO, MDO/MGO, EN590	GWP (CO_2, CH_4, N_2O), Air pollution (NO_X, SO_2, PM)	GWP of the most logical LNG chains are about 10% lower than for diesel fuel chains. LNG may reduce the air pollution significantly for the 2011-2015 time frame. LNG had lower PM, CO_2 and SO_X emissions compared to Tier III diesel.	Verbeek et al. (2011)
Screening LCA	"Diesel" from SimaPro	GWP, OP, AP, EP, winter smog, METP, HTP, solid waste, material use, EDP energy use, POFP	All LCA phases should be considered as important, but with respect to different environmental impacts. Combustion of oil (operation) is the most important. In terms of GWP and AP, the operational-phase was superior in contribution	Johnsen and Fet (1999)

3.5 RESEARCH ON MARINE ENGINE COMBUSTION

The engine technology is decisive for some pollutants, e.g. CO, VOC, NO_X and PM which are derived from soot. Research show that NO_X emissions factors for medium and slow speed engines differ significantly, Richardson (2006). Other pollutants, e.g. CO_2, SO_X, PM (mainly sulfate-derived) and heavy metals are predominantly fuel based, Trozzi et al. (2009).

Very few measurements of emission factors using alternative fuels in marine engines have been published. The published studies are also varying in terms of reference fuel and engine type. Engine specification and key findings are presented from the literature available in Table 3.5.1.

Table 3.5.1: Key findings from previous research on fuel combustion performance

Engine type	Fuels analyzed	Key findings	Reference
Wärtsilä WX 28B 2-stroke engine Max. power output of 300kW at 600rpm	HFO(S= 2.06%) MGO, GTL Fish oil (FO)	PM emissions were reduced by 67% and 75%, respectively. NO_X emissions were reduced by 11% for GTL, and increased 3% with FO. CO emissions were increased by 17% using GTL, and reduced 34% using FO.	Aesoy et al. (2013)
Volvo D4 Tier 2, pleasure boat engine, Max power output of 191kW at 3,500 rpm	GTL(Ecopar) RME (rape oil) VSD50[1]	PM emissions were significantly reduced, with 24% for GTL, and 38% for RME. NO_X emissions were reduced by 7% using GTL, while it increased 9% for RME. GTL reduced CO emissions with 10%, while RME increased it with 24%.	Cerne et al. (2008)
One single-cylinder test engine. Max power output of 400kW at 750 rpm	HFO(S=2.17%), MGO, Palm Oil, Animal fat, Sunflower oil, Soy bean oil	CO_2 , CO, and NO_X did not vary significantly between HFO and low- sulfur fossil and biogenic fuels. PM emissions relative to HFO are reduced to 6-25% for MGO, and to 6-60% for biogenic fuels, assessing different engine loads.	Petzold et al. (2010)

The following observations can be made from the studies:

- *PM emissions are significantly reduced for the alternative fuels in both studies, even compared to low sulfur-fuels (VSD50).* This can be explained by the close to non-existing sulfur content of the alternative fuels.
- *Synthetic fuels reduced the NO_X emissions, while the biofuels increased it.* Aesoy et al. (2013) explaine the decreased NO_X emissions from GTL with the increased cetane number[2]. The increased NO_X emissions from FO are likely linked to its higher combustion temperature caused by presence of fuel-bound oxygen.
- *Alternative fuels have a varying effect to CO and CO_2 emissions.* This can be explained by differences in LHV, carbon/hydrogen-ratio and fuel conversion efficiency.

Another study on climate impact of biofuels in shipping was presented by Righi et al. (2011). HFO was used as a reference fuel in comparison with the low-sulfur fuels MGO, palm oil and soy oil. The research shows that by substituting conventional fuel with low-sulfur fuels, a significant reduction in surface level sulfate concentration could be achieved, i.e. 40-60%. The reduction of sulfur oxides, in this case SO_4, leads to an increase of NO_3 due to

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[1] Volvo Standard Diesel, 0.005% sulfur content (50 ppm).

[2] Cetane number (CN), is a measurement of the combustion quality of diesel fuels during compression ignition.

chemical follow reactions [3]. The indirect effect of PM emissions on climate, i.e. aerosol effects and cloud formations, did not differ significantly between low sulfur fossil fuels and low sulfur biofuels.

A study on marine engines using biofuel blends have been carried out by Jayaram et al. (2011). The study compared 20% and 50% diesel blends (B20 and B50) with HFO using a EPA Tier 2 marine propulsion engine on a ferry. No statistically significant change in NO_X emissions were found. A 16% and 25% reduction of $PM_{2.5}$ mass emissions were obtained in the study by use of B20 and B50 respectively. The study also found a significant number of nuclei mode particles (<50 nm) and a smaller mass mean diameter with increasing blend-levels of biodiesel.

The difference in the emission totals for biofuels with respect to standard fuel is a consequence of their composition, which is characterized by a low carbon content, a high oxygen content, and a negligible sulfur content, Righi et al. (2011). Emissions of NO_X are mainly controlled by the engine combustion temperature, which is likely why NO_X emissions do not differ much when comparing biofuels and conventional fuels.

The limitation of these studies is the lack of synthetic biofuels, see Section 2.7.3.

There are a lot more literature available on emissions generated by combustion on conventional fuels, such as HFO and MGO/MDO. For more information, see Kasper et al. (2007), Winnes and Fridell (2009), Sarvi et al. (2008) or the EMEP/EEA emission inventory guidebook; Trozzi et al. (2009).

A study by Chryssakis et al. (2011) presented indicative combustion values for the fuels assessed. See Table 3.5.2. The table presents the emissions in percentage points, using HFO/MDO with a sulfur content of 1% as reference. It should be noted that the values can vary, depending on the specifics of the propulsion technology used.

Table 3.5.2: Emissions and environmental hazards

Fuel	CO_2	NO_X	SO_X	PM	Leak/Spill
HFO/MDO	100	100	100[4]	100	Significant clean-up efforts
LNG	75	10-80	<1	<30	Forms vapor cloud
Methanol	95	70-90	<1	<5	Forms vapor cloud
DME	89	40-60	<1	<5	Forms vapor cloud
Fischer-Tropsch	96	80.85	<1	≈ 120	Significant clean-up efforts

Additionally notice should be made to the fact that multiple studies have been made on engines applied for vehicles and trucks, Bright and Strømman (2009), Börjesson and Mattiasson (2008), Huo et al. (2008). Heikkilä et al. (2009) experienced, similar to the results of the marine studies, an increase of NO_X emissions using RME, and a decrease using GTL fuel compared to the ultra low sulfur fuel EN590. The PM emissions were reduced with 36.0% and 37.8%, respectively.

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[3] With less SO_4 is present in the troposphere, less ammonia is involved in the neutralization reaction forming ammonium sulfate. This excess ammonia thus becomes available for formation of ammonium nitrate.

[4] Reference taken for 1% sulfur fuel. It will be proportionally higher or lower, depending on the actual sulfur content of the fuel

4

METHODOLOGY

4.1 INTRODUCTION

In this chapter Life Cycle Assessment will be described as an environmental impact assessment tool. The following section will briefly describe the framework for conventional LCA. Section 4.3 will discuss the variations of LCA methodology, and then the challenges and limitations of the chosen tool for this study will be discussed in in Section 4.4. The collection of data for this study will be described in Section 4.6, and the use of tools to process the data will be clarified in Section 4.7.

4.2 LIFE CYCLE ASSESSMENT

LCA is an analyzing tool enabling the quantification and evaluation of the environmental performance of a system consisting of multiple technical processes, with a cradle to gate perspective. LCA makes it possible to compare the environmental impact potential of different product or services providing a similar service.

Standards for the LCA procedure have been published as a part of the International Organization for Standardization's 14000 Environmental Management standards, latest in 2006 (ISO 14044). In ISO 14040 LCA is defined as the *compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle*. The framework for conventional LCA is worldwide accepted, and the methodology for different life cycle impact (LCI) tools, with the origin of LCA, constantly evolving. The structure of this LCA will follow the Handbook for LCA by Guinée (2002).

LCA is generally structured in four phases:

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation

While the three first stages must be performed consecutively, the interpretation-phase can be carried out intermediate to the others. As illustrated by Figure 4.2.1, the LCA is an interactive process, opening up for revising the four phases when it is considered necessary.

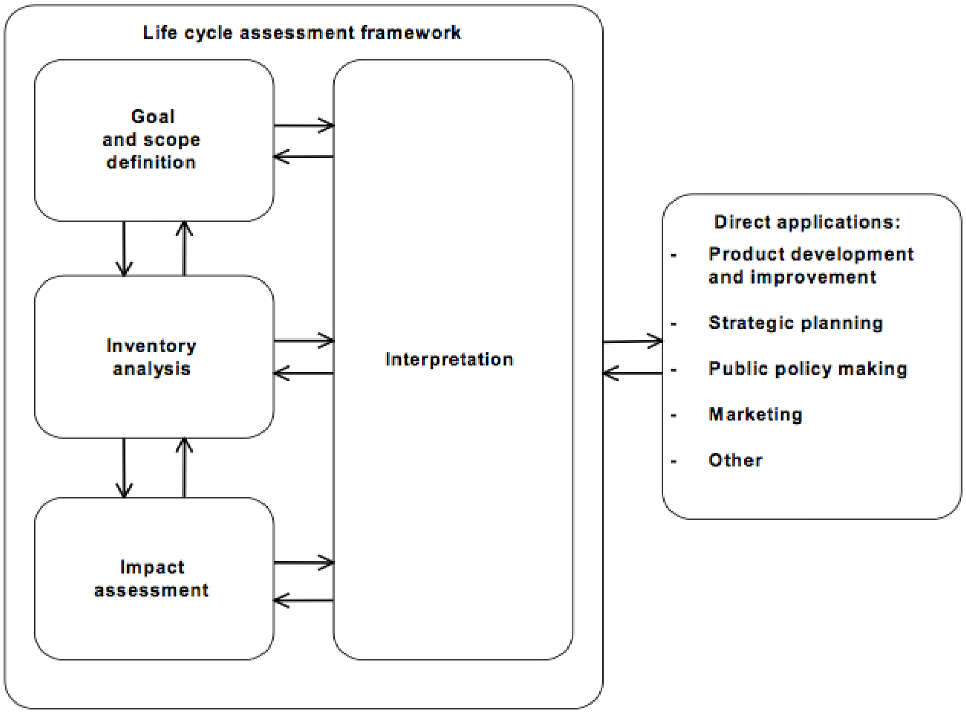

Figure 4.2.1: The overall framework of LCA and its applications, ISO14040 (2006)

The first stage aims to define the system analyzed; In *the goal definition*, the objective of the study is stated, explained and justified. The *scope* definition establishes the main characteristics of the intended study, e.g. temporal, geographical and technological system boundaries. The scope will define if it will be carried out a cradle to grave or cradle to gate analysis. In a cradle to grave perspective one analyze the impact of a product from the beginning of its source gathering processes, through the end of its useful life, to disposal of all waste products. The cradle to gate analysis only considers the processes up to the delivery of the service or product, and does not cover the entire life cycle of the system. The *functional unit* of the assesses system will be defined. The functional unit quantifies the performance of the system, serving as a reference point for the commodity flows and enables a comparing analysis.

The product system is defined in *the Life Cycle Inventory Analysis* (LCI) by setting system boundaries and designing of flow diagrams. Flow diagrams show how the processes that constitute the system are defined by environmental and economic flows. The processes are generally illustrated by boxes, while the flows are expressed by arrows. Economic flows connect processes, e.g. a power station supplies a factory with electricity, while environmental flows are substances and materials directly extracted or submitted to the environment, e.g. exhaust emitted from a factory, or iron ore extracted from a mine. A unit process is defined as *a set of interrelated or interacting activities that transforms inputs into outputs*, ISO14040 (2006).

Figure 4.2.2 illustrates a simplified flow diagram. The blue boxes represent unit processes while red and black arrows represent associated economic and environmental flows, respectively. The red arrows can also be referred to as intermediate flows. The dotted rectangle indicates the system boundary, separating the environmental and economic environment. The process flow diagrams are illustrative and intuitive, though it has its limitations when dealing with complex systems, e.g. when the processes are interconnected and result in internal loops.

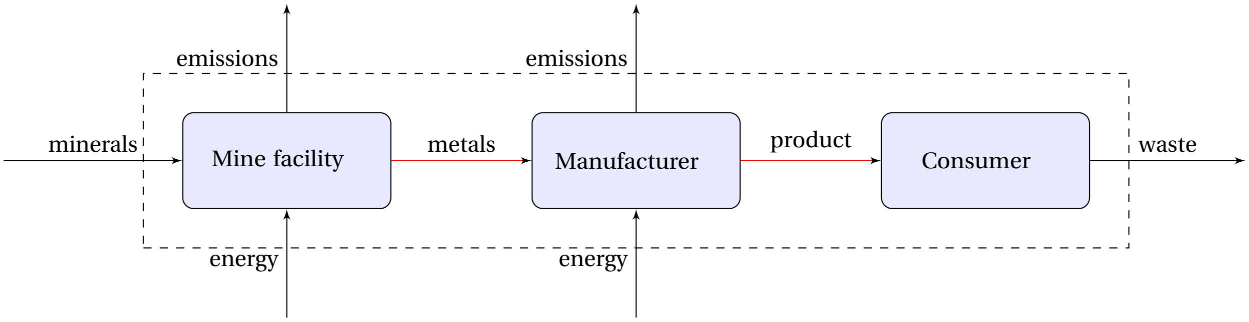

Figure 4.2.2: Simplified flow diagram

The key task of the Inventory Analysis is to make a model of the system where all economic flows are intermediate steps in a transformation of environmental inputs into environmental outputs. Setting up inventory data, by collecting and quantifying data for all the processes described in the flow diagram, can be one of the most labor- and time-intensive stages of a LCA, Finnveden et al. (2009).

In the Inventory Analysis, one often refer to *foreground* and *background* systems. The foreground system is made up by processes that are modeled with data that is complied specifically for the given study, while background system includes processes that are modeled based on generic databases, Strømman (2010).

The result of the Inventory Analysis is a comprehensive table of accumulated emissions of pollutants and extracted resources for the system, normalized to the functional unit. *The Impact Assessment* then aims to interpret and aggregate the data from the inventory table, and present the results in an informative way for the reader.

This is done by expressing the relative importance of physical environmental flows to environmental *impact categories*. The impact categories are effects on the environment that is considered as caused by particular pollutant emissions or resource extractions. The environmental relevance of the emissions and extractions can be quantified by an indicator, which is in LCA referred to as a *characterization factor*. For example, what effect CO_2 emissions have on the impact category climate change, is indicated by the characterization factor global warming potential (GWP). The characterization factors are relatively certain, but the informative value can be low. Impact categories are therefore used to present the environmental impact of processes and products.

Commonly used impact categories in LCA with the associated characterization factors and determining parameters are presented in Table 4.2.1.

Table 4.2.1: Common impact categories with characterization factors

Impact Category	Indicator	Parameters
Climate Change	Global warming potential (GWP)	CO_2 , CH_4, CFC, HCFC
Ozone layer depletion	Ozone depletion potential (ODP)	CFC, HCFC
Human toxicity	Human toxicity potential (HTP)	Metals, organic substances, pesticides
Eco toxicity	Human toxicity potential (HTP)	Metals, organic substances, pesticides
Acidification	Acidification Potential (AP)	SO_2 , NO_X, NH_3

The results in this study are presented by 18 impact categories, representing a midpoint indicator of a certain form of environmental impact, e.g. climate change and ecotoxicity, after the *ReCiPe hierarchist impact assessment model*. With this midpoint approach, also called problem-oriented approach, contribution of each substance and resource, in this study referred to as stressor, are evaluated and the assessments are aggregated based on equivalency principles. The calculated characterization factors for the midpoint indicators, published by the IPCC, have a relative low uncertainty and a high level of acceptance, Goedkoop et al. (2009). The hierarchist perspective is based on the most common policy principles with regards to time frame and other issues. i.e. the midpoint impact category climate change has a 100 years perspective and the human-, terrestrial-, and freshwater toxicity is calculated on an infinity time range. Further details of the ReCiPe hierarchist impact assessment model are given in the literature, Goedkoop et al. (2009). The Handbook of LCA by Guinée (2002) states that the midpoint approach is *deemed the best practice for impact assessment.* An alternative approach could be Eco-indicator 99, developed by Goedkoop and Sprensma, which is using endpoint impact categories.

In the final stage of the LCA analysis, *the results are interpreted and discussed.* This is often done through a Contribution Analysis where impact results are broken down to assess the contribution from each unit-process and type of stressor in the analyzed system. Sensitivity Analysis can be performed to assess how dependent the results are on different parameters from the inventory analysis.

For the mathematics of LCA please see referred literature, Strømman (2010).

4.3 VARIATIONS OF LCI

There has been published multiple articles about the LCA methodology, and the development within the field has been substantial. Different methods are available for LCI, and they differ in scope, certainty and labor intensity etc. It is therefore given that they also may generate significantly different results. This makes it necessary to highlight the challenges and limitations of the chosen method for this study. The main methods of LCI will now be briefly presented with the respective advantages and drawbacks. The challenges and limitations of the applied method for this study will be further discussed in Section 4.4.

Process-based LCA is an environmental assessment tool where unit processes that describe the system are connected with physical quantified input and output flows. This means that all the economic flows, as described in the previous section, is expressed in form of energy or material use. The tool opens up for a high level of detailing, making it suitable for comparing products or systems. One of the main challenges with process-based LCA is the incomplete system boundaries. Processes excluded in the inventory, also referred to as cut-offs, may lead to uncertain and biased results.

Environmental Input and Output Analysis (EIO) has a wider scope compared to the conventional process based LCA. EIO quantifies the environmental impacts generated by economic activity. The economic system is described by economic interactions between industries, defined by national statistics of multiple establishments performing the same economic activities, United Nations (1999). By summing the amount of pollutants emitted or natural resources consumed to produce one unit monetary output of each industry, the environmental impact generated by a demand put on the economic system can be obtained.

The weakness of the EIO as an environmental impact assessment tool is the high level of aggregation and the generalization of multiple companies and industries, excluding the possibility to assess the impact of specific processes or products. Considering the goal and scope of this assignment, it is assumed that an EIO will not hold the required level of detail to differentiate the environmental impact potential of the different fuels and ship characteristics. For example, the production method for biofuel is considered to have major impact on the final environmental performance of the fuel. Still, by using economic values from the agricultural sector it is impossible to distinct a sugar cane feedstock from agricultural waste, other than in terms of costs.

Hybrid-Life Cycle Assessment (HLCA) aims at increasing the analytical benefits and reduce the limitations by combining process-based LCA and EIO. Suh (2004) states that HLCA *overcomes the problem of incompleteness of the system.* There are various forms of HLCA. Suh and Huppes (2005) distinguished HLCA as tiered hybrid analysis, IO-based hybrid analysis, and integrated hybrid analysis. These three types of HLCA will be briefly explained in the following and illustrated by figure 4.3.1.

- *Tiered HLCA* treat the process-based and the Input and Output (IO)-based systems separately, by adding the results from the two LCIs together. This requires high caution when the system boundaries are set to avoid double counting. Ideally, the economic activity should have been modeled by processes, and then be subtracted from the IO-system.

- *IO-based hybrid analysis* aims to selectively disaggregate the aggregated input-output data or create hypothetical new commodity sectors to reduce the uncertainty of conventional EIO. To further identify the environmental impact of a specific product or process, the tiered approach will be applied for the use and disposal-phase of the life cycle.
- In *Integrated* HLCA , the major part of input and output flows are represented by the process-LCA based system, and cut-offs are linked with the IO-based system, as illustrated in Figure 4.3.1. This maintains the detailed unit process level of information while one includes the surrounding economy in the analysis.

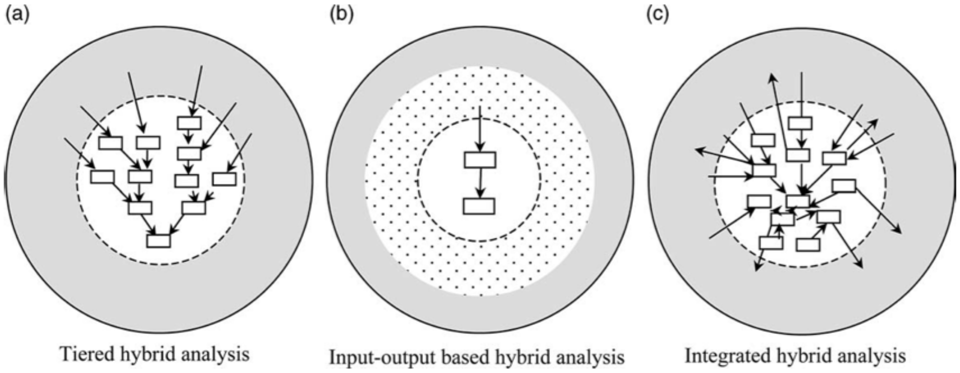

Figure 4.3.1: Interactions between process-based system and IO-based system of hybrid analyses, Suh and Huppes (2005)

As earlier mentioned in section 3.2, Life cycle assessments are often divided into *attributional* and *consequential* LCA.

- The *attributional* LCA is about how to attribute the total environmental impact to existing products or systems, and can be further described as an *ex-post* question. The attributional analysis will for example try to identify the individual contribution of all processes to the total environmental impact of the facility. A complete system boundary is therefore crucial in this form of analysis.
- The *consequential* LCA aims at describing the consequences in environmental impacts caused by a certain change in e.g. policy, technology or production/consumption patterns. For example; what will be the consequences of replacing a cities car fleet with electrical vehicles? The consequential LCA forms an *ex-ante* question, aiming at providing the consequences of future event.

Considering the goal of the study, a consequential LCA will be performed. The advantages of such an analysis is that it includes only the processes of the system that will differ between the alternative systems/fuels, and is therefore less time and labor intensive, making it better suited for comparing the environmental performance of different marine fuels.

4.4 CHALLENGES AND LIMITATIONS

The results from the LCIA addresses only the environmental issues that are specified in the goal and scope. As mentioned in the previous section, the incomplete system boundaries are one of the main challenges with process-based LCA. A number of so-called LCA have been published by producers of consumer products, in an attempt to promote the green policy of their company. These reports must be met by the highest caution, as processes excluded in the inventory may lead to uncertain and biased results.

It is however impossible to include all processes linked to a product or system in a LCA. Both due to the lack of data and the time and labor intensity of the task. It has therefore been given guidelines of what processes to exclude and which to include in the life cycle inventory.

By solely using process-specific data for the LCA the system analyzed is treated like an independent system, rather than seeing it as an embedded piece of the economy. The method excludes the fact that activity within an industrial sector are interrelated with several other sectors, and may cause ripple effects in the economic system. The method rarely accounts for service inputs, for instance are labor and processes down stream in the systems often excluded. For example; iron can be included as an input to a component in the system, but the energy consumed in the production-phase of that component might be excluded due to limited data or for simplification.

One challenge of LCA is the issue of allocation. As a process might have multiple outputs, for example a oil refinery produces different types of petroleum products, the emissions related to the process must be allocated in some way. There are three main approaches for allocation: the disaggregation approach, the substitution approach and partitioning approach. Please see referred literature for description of the methods, Strømman (2010).

4.5 APPLYING LCA FOR THE MARINE SECTOR

Process-based LCA is both a useful and right tool to use when alternative marine fuels shall by assessed. A system can be modeled with processes, input-, output and intermediate flows. Each environmental and economic flow is bound to the characteristics of the process.

An example related to alternative marine fuels is the operation of a ship within the port, which can be modeled as one unit process. The product delivered by the process can either be measured by the energy output of the propulsion during the operating time, or by the number of hours it is operating. Both factors are given by the operation profile of the ship. What input flows that are required by the process in order to cover its demand, are in this case depending on factors such as engine efficiency and fuel characteristics.

Strictly speaking, the operation of a ship does also require some kind of maintenance of the ship, labor work, a ship contraction, ship applications and so forth. To model an exact system, with all its inputs and outputs, a major amount of data, and not at least labor are required. It might however be that some of these inputs and their background processes are not decisive for the final result. Even though there are no general rule for what processes to exclude, the ISO standard of LCA (ISO 14040) opens up for narrowing the system boundaries when needed. ISO 14040 states that *The level of modeling detail that is required to satisfy the goal of the study determines the boundary of a unit process...resources need not be expended on the quantification of such inputs and outputs that will not significantly change the overall conclusions of the study*.

Previous studies could be used to give some indication of which life cycle stages, i.e. processes that are less important to the overall environmental performance of the system. The aim of the LCI must be to spend effort on those processes along the life cycle that cause a difference in environmental impact compared to the reference fuel. The construction of the fuel refinery may for example play a close to negligible role in the big picture. To use the same unit process from a background database for such processes when modeling the life cycle of the different fuels is one way of simplifying the system without removing the possibility to compare the impact of the different fuels. The processing of the different fuels and the emission factors related to combustion of each fuel play however a crucial role for the total environmental impact potential of the entire system.

The methodology behind LCA provides scientists with useful tools to relate environmental impacts back to the composition of the modeled system, which will prove useful in LCA studies of shipping and marine fuel alternatives:

- A *Contribution Analysis* show the distribution of impact potential between the processes modeled in the foreground, and those processes which are modeled in the background system. This form of analysis gives valuable information about what processes along the fuel chain are important, and give an indication of which factors are decisive for the system's environmental performance.
- A *Structural Path Analysis* (SPA) is another analysis which has a similar purpose; it relates impact to specific process-chains. While the Contribution Analysis tells you which process eventually contributes to the greatest

impact, the SPA will let you know how this unit process is connected to the functional unit through the intermediate flows of the system.

- The Contribution Analysis also provides each stressors' relative share of the impact potential. This information can for example be used to assess the relative importance of the emission factors applied for each fuel.
- *Taylor Series Expansion* (TSE) is one way of relating impact to each tier of the system. The functional unit will place a demand on processes modeled in the foreground, which again will place a demand on the background process. Eventually, the impact of the functional unit will be related to resource extraction. The TSE provides information of the relevance of the different tiers; how much of the impact is generated upstream and what share of the impact that can be related to background processes far downstream.

In order to utilize these tools, and for making the modeled system applicable for various vessels, the Life Cycle Inventory should be modeled in a flexible way, where the intermediate flows of the system are bound to the key factors. This can illustrated by a simplified flow diagram, which is presented by Figure 4.5.1.

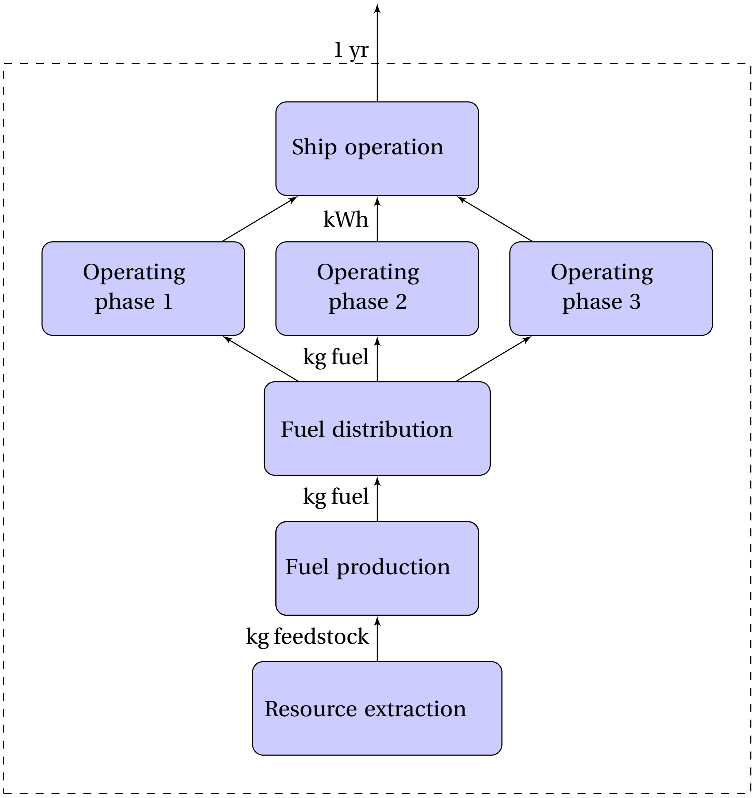

Figure 4.5.1: Flow diagram, marine fuel life cycle

In Figure 4.5 unit processes are modeled as blue boxes, while the economic flows are modeled with arrows. The flow diagram includes foreground processes, while the dotted line indicates the system boundary to the environment.

By defining the outputs of each process one can facilitate or exclude adjustment of the system. As each operational-phase is Figure 4.5 modeled as a processes delivering a energy content in terms of propulsion output, given in kWh, various operational patterns can be implemented as the output depends on the hours of operation and propulsion power.

By setting the storage facility's or delivering freight ship's output unit as one kg of fuel, the specific fuel consumption, given in kg/kWh, will determine the intermediate flow between the operational-phases and fuel supply. This creates a flexible system which can account for engine efficiency and lower heating values of the applied fuel.

This shows how the LCA tool can be applied for unique systems for evaluating a variety of research questions.

4.6 COLLECTION OF DATA

The quality of a LCA is depending on good data, and an inclusion of all processes required to present a comprehend and unbiased result.

To represent foreground and background processes in the system, unit-processes from the Ecoinvent 2.2 database are used in the extent the data are found accurate and representative for the scope. The Ecoinvent database is the world's leading database with consistent and transparent, up-to-date LCI data. The datasets are based on industrial data and have been compiled by internationally renowned research institutes and LCA consultants.

The process-data available in the Ecoinvent 2.2. database for shipping operations are however limited. For water transportation, data has been aggregated to fit four generalized vessels, and the impact of the operation is calculated in terms of tkm. The lack of specific emission data related to engine type, efficiency and load profile therefore makes the processes inapplicable for the objective of this study.

In compliance with the goal of the study, engine specific data, i.e. emissions factors and efficiency, obtained through direct measurements in steady-state engine operation, have been used to the highest possible degree. Other emission factors have been taken from the literature, mainly from Trozzi et al. (2009), which contains the same emission factors used in modeling the shipping transportation by Ecoinvent 2.2.

4.7 USE OF DATA TOOLS

The life cycle impact assessment was carried out by the software Arda 16.1. Arda is a LCA software developed at the Industrial Ecology Department at the Norwegian University of Science and Technology. The software includes a Excel worksheet, where the system processes and flows are to modeled by using substances, processes and resources from the Ecoinvent 2.2 database.

MATLAB v. R2011b, a product by MathWorks, was used to compile the technology and stressor matrices and perform the impact assessment making use of the ReCiPe characterization matrices. MATLAB is a numerical computing environment, well suited for solving large matrix computations. Results were saved in Excel format, allowing further processing and layout.

4.8 KEY ASSUMPTIONS AND ALLOCATION CHOICES

4.8.1 CARBON NEUTRALITY

As mentioned in the Scientific Background, Section 2.6.3, the convention of carbon neutrality for biofuels is widely applied in LCA studies. For the base cases, this will also be applied in this study by assuming that the amount of carbon contained in woody biomass connected to the functional unit (as inputs to energy production) is the amount of biogenic carbon emitted per functional unit.

The software used for the Life Cycle Impact Assessment, Arda Gui 16.1, is solving this by applying a GWP characterization factor of zero to environmental flows of biogenic CO_2. This simplifies the modeling, as there is no need for manually balancing the carbon along the life cycle of the system.

4.8.2 INFRASTRUCTURE

The LCA framework opens up for including processes related to construction, operation and demolition of processes. The study is a comparative LCA. In order to simplify the systems assessed, processes that are found inhomogeneous along the different fuel cycles are as far as possible included. The construction of the different fuel production facilities will be modeled using Ecoinvent 2.2 unit processes. Modifications have only been applied to the LNG facility, where storage tanks have been included.

Construction and maintenance related to the operating vessels are excluded, because it is assumed that the environmental impacts will be equal for the different fuel paths. In other words, it is assumed that the application of the alternative fuels will not lead to any noteworthy modifications of the ship's construction and maintenance in respect to environmental impacts.

The lifetimes assumed of the fuel plant facilities are presented in Table 4.8.1.

Table 4.8.1: Applied lifetime of fuel production facilities

Fuel	Lifetime	Reference
HFO	30yr	Jungbluth (2007)
MDO/MGO	30yr	Jungbluth (2007)
LNG	30yr	Assumption
Methanol	50yr	Jungbluth et al. (2007a)
DME	20yr	Jungbluth et al. (2007b)
FT-diesel	20yr	Jungbluth et al. (2007b)

A construction coefficient enables us to calculate the environmental impact associated with construction per functional unit. The construction coefficient can be calculated by dividing the total environmental load (as demand on resources and processes) by the total number of units produced throughout the lifetime of the facility constructed. The construction coefficient will then represent the amount of construction required per unit output of the process.

4.8.3 DISTRIBUTION OF FUELS

It is assumed that the impact of distribution of the respective fuels is minor to the total environmental impact of the systems modeled. The distribution process is therefore characterized by rough assumptions and narrow scope.

The distribution of the alternative fuels are modeled by using the unit process *transoceanic freight ship* from the Ecoinvent database. The process includes the following:

- construction and demolition of the freight ship
- operation and maintenance of the freight ship
- disposal of bilge oil
- lorry transportation
- port facilities

No additional emissions or resource used are modeled in addition to those who are already implemented by the background processes, unless it is specified in the Life Cycle Inventory.

It is assumed that the fuel tankers modeled for the distribution of the alternative fuels are returning to the fuel production facility empty, after unloading, in a so-called ballast transit.

It can be calculated from the operational profile of the container ship modeled in this study, that the specific fuel consumption is slightly increasing by 3% when the ship goes ballast transit, compared to normal transit operation.

The total amount of tonnes of goods transported over a certain distance (tkm), is therefore doubled, in order to include the impact of the ballast transit of the fuel tanker, since the Ecoinvent database does not include ballast transit as an own unit function.

It is assumed that the fuel tanker will be fully unloaded, with the exception of LNG-tankers, which requires a certain amount of fuel remained in the tanks on the ballast transit due to technical specifications. Here the magnitude of transportation will be derived based of the LNG content in the storage tanks. This will be further explained in the Life Cycle Inventory, Section 5.2.3.

The distribution of conventional fuels are included by using the Ecoinvent's fuel unit processes *at regional storage* using European average values. No additional emissions and resource use are added to the process.

4.8.4 ALLOCATION OF BY-PRODUCTS

Environmental impacts related to the LNG production has been allocated by the partitioning approach based on the energy content of the plants' multiple products. Where production facilities have been modeled solely based on previous LCA studies, the allocation of impact will follow the assumptions made by the studies, unless nothing else is specified in the Life Cycle Inventory. For unit processes obtained from the Ecoinvent database 2.2 this implies a partitioning after the market value of the by-products.

4.8.5 ESTIMATING DIRECT EMISSIONS

As specified in the goal of the study in Section 1.2, the study aims to include specific information about chosen marine vessels, e.g. fuel and engine type and operational patterns, which are decisive for the energy efficiency and combustion-related emissions.

To estimate the emissions during combustion, also called Tank-to-Propeller (TTP) emissions, the Tier 3 approach developed by Trozzi et al. (2009) for EMEP/EEA emission inventory guidebook 2009 has been used in this study.

The Tier 3 approach calculates the direct emissions from shipping by summing the emissions on a *trip-by-trip* basis. When the fuel consumption for each operational phase is known, the amount of emitted pollutant can be computed. The emissions from each trip can be expressed as in equation 4.8.1:

$$E_{\text{Trip}} = E_{\text{Hotelling/Maneuvering}} + E_{\text{Cruising}} + E_{\text{Ballast transit}} \tag{4.8.1}$$

The total direct emission from a vessel can then be obtained by multiplying the emission with number of trips per year.

Based on propulsion power for the different operation phases, engine efficiency, duration, and the lower heating value (LHV) of the fuel used, the total fuel consumption for the trip can be obtained. By multiplying the fuel consumption with the respective emission factor, it is possible to calculate the total direct emissions from the vessel.

In order to calculate the emissions, the procedure for *estimating emissions based on engine power* has been used with some modifications, following the given steps:

1. Obtain ship movement data, i.e. place of departure, place of arrival, time of departure and time of arrival.
2. Determine the sailing route and distances between the ports
3. Characterize each ship by ship category (e.g. container, general cargo, passenger vessel), engine type, main and auxiliary engine propulsion at different operational phases.
4. Determine amount of trips per year for the specific ship
5. Determine total sailing time for each operational phase

6. Calculate emissions for each ship category and engine type/fuel class

The sixth step is expressed by equation 4.8.2.

$$E_{Trip,i,j,m} = \sum_{p} \left[T_p \sum_{e} \left(\frac{3.6 \times P_e \times EF_{e,i,j,m,p}}{\eta_{e,p} \times LHV_m} \right) \right] \tag{4.8.2}$$

where:

E_{Trip} = emissions over a complete trip [kg]

EF = emission factor [kg/kg fuel]

P = propulsion power [kW]

T = duration [hours]

LHV = Lower heating value [MJ/kg fuel]

η = engine efficiency

e = engine category (main, auxiliary)

i = pollutant (e.g. CO_2, SO_X, PM)

j = engine type (high-, medium-, slow-speed diesel engine)

m = fuel type (e.g. HFO, MDO, LNG)

p = operational phase (e.g. cruise, hotelling, manouevring)

This procedure has been integrated with the life cycle-based approach presented in SectionmarineLCA. This implies that the calculated emissions are included in the model in relation to the output of the process/operational phase, which in this case is given in delivered propulsion energy.

The emissions are modeled as *stressors*, see Section 4.2, using the Ecoinvent 2.2 database. Where it is possible, pollutants emitted at harbor, during maneuvering, are characterized as *emissions to air, high density* while the emissions occurring at sea, during transit, are characterized as *emissions to air, low density*.

5

LIFE CYCLE INVENTORY

5.1 INTRODUCTION

In this chapter the systems to be analyzed will be defined together with the system boundaries. Flow diagrams with unit processes of the systems will be presented. The operational profile of two unique vessels, together with derived engine efficiencies and emission factors will be used in assessing the environmental impact of the operational-phase of the life cycle. The inventory data of each fuel route will be presented separately. Based on the assumptions presented in Methodology Chapter, Section 4.8, the final inventory is quantified as inputs and outputs of materials, energy and pollutants.

The fuel life cycle will be modeled as suggested in the Methodology chapter, Section 4.5. A foreground matrix of each fuel system is presented in Appendix 10.1.2 for each vessel type. The complete LCI for each system is to be found in Appendix D.

5.2 MODELING OF FUEL ALTERNATIVES

5.2.1 HFO PRODUCTION AND DISTRIBUTION

The LCI of the production and storage of HFO has been modeled solely by using the Ecoinvent 2.2 database and its inventory of *heavy fuel oil*. Since the LCA of HFO functions more as a reference point, time and labor resources have been prioritized to model the life cycle paths of the alternative fuels.

The process data for HFO include the following life cycle stages:

- oil field exploration
- crude oil production
- long distance transportation
- oil refining regional distribution

For all these steps, air- and waterborne pollutants, production wastes as well as energy and working material requirements have been inventoried, Jungbluth (2007).

The oil exploration data are mainly based on emission data from North Sea exploration, which is found suitable for the scope of the study. The inventory data for other process stages are given as an European average. It has not been prioritized to modify the processes, e.g. it is assumed that the regional storage is close to the ports.

The life cycle chain of the HFO is illustrated in Figure 5.2.1. In order to simplify the system the extraction of crude oil and refinery processes are integrated in the life cycle chain as a single unit process.

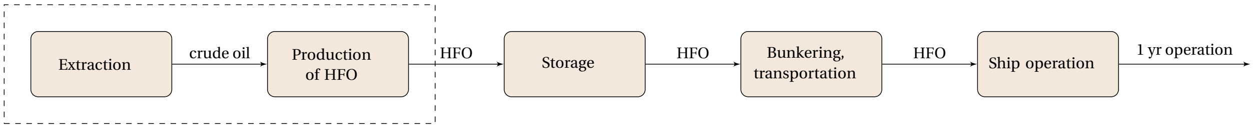

Figure 5.2.1: Life cycle chain of heavy fuel oil

The emissions related to transport and bunkering from the regional storage to the ship in operation are not accounted for. It is assumed that the regional storage is close to the port, and the excluded impacts are considered insignificant for the total environmental impact potential.

The complete LCI for HFO production and distribution is presented in Appendix D.

5.2.2 MDO/MGO PRODUCTION AND DISTRIBUTION

As with the MDO/MGO, the life cycle of the production and storage of MDO/MGO is based on the Ecoinvent 2.2 database. The methodology and assumptions behind the LCI of the process *light fuel oil* at refinery and storage is presented in Jungbluth (2007). No distinction has been made between MDO and MGO in the inventory.

For the life cycle chain of the MDO/MGO see Figure 5.2.1. In order to simplify the system the extraction of crude oil and refinery processes are integrated in the life cycle chain as a single unit process.

As for the system description of the HFO-route, the emissions related to transport and bunkering from the regional storage to the ship in operation are not accounted for. As for the HFO it is also assumed for the MDO/MGO that the regional storage is close to the port, and the excluded impacts are insignificant for the total environmental impact potential.

The complete LCI for MDO/MGO production and distribution is presented in Appendix D.

5.2.3 LNG PRODUCTION AND DISTRIBUTION

The production of LNG, is in this study set to the Melkøya LNG plant, outside of Hammerfest; the first LNG export facility in Europe. The gas exploration is the first in the Barents Sea. It is believed that the plant represent a modern facility, representative for future LNG production in case of efficiency and environmental impacts.

Figure 5.2.2: Melkøya LNG plant and export facility, Wikimedia Commons

The production facility is invisible from the surface, located on the seabed between 250 and 345 meters below sea level. Natural gas liquids and condensate are transported through the world's longest multiphase pipeline of 143 km, to the liquefaction plant at Melkøya Island, Nilsen (2012). The natural gas contains between 5-8% carbon dioxide, which is separated from the gas by using amines. The CO_2 is then reinjected into a sand stone formation, 2,600 meter below sea level, through a 153km pipeline. The injection and storage of CO_2, started in 2008. The annual storage capacity is 700,000 tones of CO_2, Statoil (2008).

The gas fields Snøhvit and Albatross are currently being exploited, while the gas field Askeland will start producing in 2014/2015. The complete facility will in the future comprise 20 wells, including one well for reinjecting CO_2 to storage.

The facility is operated by Statoil ASA, which claims the plant to be *"the world's most efficient LNG liquefaction plant"*, Nilsen (2012). 243 kWh is used to compress one tonne of LNG. The LNG is stored in two LNG tanks with a storage capacity of 125,000 m^3, and a diameter and height of 74 m and 48.70 m, respectively, Technology (2008).

The life cycle chain of the LNG is illustrated in figure 5.2.3. In order to simplify the system, due to the scope of the study, the extraction and production of LNG will be integrated in the life cycle chain as a single unit process.

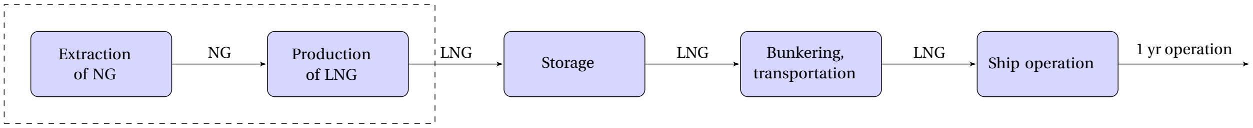

Figure 5.2.3: Life cycle chain of LNG

The data for the facility's energy and resource use, waste treatment and emissions to air and water are taken from the annual report of Snøhvit from 2011, Statoil (2011). The data is presented in Table 5.2.1. It is assumed that the energy use and emitted pollutants associated with loading the LNG cargo ships are accounted for in the report. All inputs and outputs of the facility is modeled using Ecoinvent unit processes, resources and stressors. Due to lack of specific unit processes in Ecoinvent 2.2, there has been made no distinction between waste for deposition and waste for recovery, and all waste is allocated to *waste treatment for deposition* processes. Other simplification considering using of amine and caustics have been made.

The standard practice applied for boil-off gas at the Melkøya facility is not known. There has been made no modeling of the BOG handling at Melkøya LNG plant, and it is assumed that direct and indirect emissions due to BOG at the facility are counted for and included in the annual report of resource use and pollutants emitted.

The production in 2011 resulted in 3,150,000 tonnes of LNG, where liquefied petroleum gas (LPG) and condensate are byproducts from the liquefaction process. The resources consumed and emitted pollutants in the construction and operation of the plant are allocated between the three products after energy content. The derivation of the allocation factor is given in Table 10.1.10. A life time of 30 years of the facility is assumed in the calculation of the construction coefficient.

The respective storage tanks at the facility have the following capacities and dimensions:

- 2 LNG tanks 125,000 m^3 , diameter 74m, height 48.70m
- 1 condensate tank 75,000 m^3 , diameter 60m, height 42.30m
- 1 LPG tank 45,000 m^3 , diameter 50m, height 37.90m.

It is assumed that the tanks are insulated by 2 meters of concrete and stainless steel, with the relationship of 90% and 10%, respectively. The tanks are illustrated in Figure 5.2.4. The storage tanks at the facility have been modeled by production and disposal of the materials required, using Ecoinvent unit processes. It is assumed that the concrete is extracted and produced at Meland industrial park, which is within a 2 km distance from the LNG facility. The impact related to transportation of the concrete is therefore assumed negligible, and thereby not included in the report. It is also assumed that the steel is produced in the local area, and the transportation of the material is not included. The energy use related to the actual building of the storage tank is not included.

Table 5.2.1: Annual report Melkøya LNG plant, 2011

	Environmental flow	Value
Energy consumption:	Electricity	105 GWh
	Flare gas	1,020 GWh
	Fuel gas	3,260 GWh
	Diesel	1 GWh
Utilities:	Amine	64.2 m^3
	Caustics	246 m^3
	Monoethylene glycol	850 m^3
	Hydraulic fluids	48.1 m^3
	Other Chemicals	41.4 m^3
Water consumption:	Fresh water	165,000 m^3
Emissions to air	CO_2	964,000 tonnes
	NO_X	506 tonnes
	CH_4	3,070 tonnes
	SO_2	4.43 tonnes
	NMVOC	1210 tonnes
	H_2S	5.93 tonnes
Discharges to water:	Regular discharges of oil to water environment	24.10 kg
	Amine	220 kg
	Ammonium	178 kg
	Phenol	12.60 kg
	TOC	755 kg
	BTEX	55.20 kg
	Heavy Metals (Hg, Cr, Ni)	0.99 kg
	Drain water	84,100 m^3
Spills:	Oil spills	0.08 m^3
	Other spills	0.00 m^3
	Unintentional emissions of HC gas	810 kg
Waste:	Non-hazardous waste for deposition	180 tonnes
	Non-hazardous waste for recovery	961 tonnes
	Hazardous waste for deposition	881 tonnes
	Hazardous waste for recovery	259 tonnes

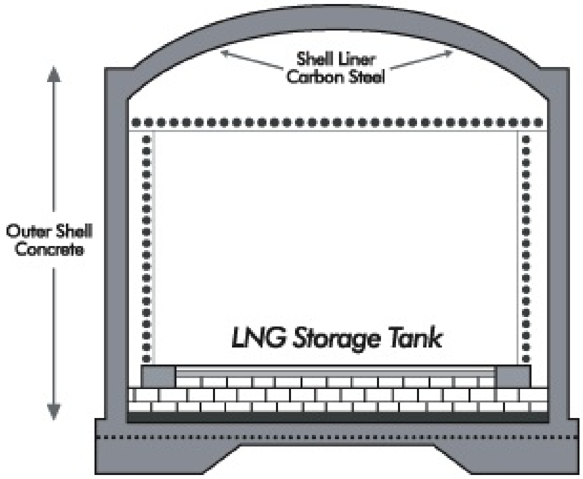

Figure 5.2.4: Illustration of storage tank at the LNG facility

It is estimated that 70 cargoes of LNG will be shipped yearly from the Melkøya facility. The Arctic Princess delivered the first LNG cargo from Melkøya to southern Europe in 2007. The 288 meters long ship was customized to transport LNG from Melkøya facility, with a total storage capacity of 145,000 m^3, divided between four spherical tanks, each with a diameter of 42 meters, Halvorsen (2007). The ship's carrying capacity will be used in creating the inventory data of the *transporation*-process. Gas leakage during bunkering, e.g. when disconnecting the filling nozzle, is excluded, as it was found negligible by Verbeek et al. (2011).

Considering the BOG formed during the transit, a daily rate of 0.15% has been used in the LCI, in accordance with typical values, Gerdsmeyer and Isalski (2005). In the base case studies, the worst-case scenario is assumed, where the BOG is directly ventilated to air. The emitted BOG is also been subtracted from the weight of transported cargo. The used mathematical equations follows below. The emitted gas is modeled by using the LNG composition used in the dual fuel engine tests by Wärtsilä. The composition is presented in Appendix 10.1.3, Table 10.1.11.

After the LNG has been unloaded at the receiving terminal, a small amount of the LNG is retained inside the cargo tanks in order to maintain the normal carrying temperature of $-163°$C. This remaining cargo is called *the heel*. 5% of the total cargo capacity is in this study retained as heel. Inclusion of the heel in the model will increase the tonnes transported per km (tkm) per delivered kg LNG. The same BOG-rate is assumed for the heel. It is further assumed that the heel remaining at arrival at the LNG terminal is reused in the next shipment.

A *transoceanic freight ship* is taken from the Ecoinvent database to represent the LNG tanker. The vessel types available in the Ecoinvent database are limited, but the ship is found to be best representative in terms of size and engine characteristics. The fuel consumed by the freight ship is modeled as *heavy fuel oil, at regional storage*. The inputs of the process are based on the Ecoinvent Database of transport of liquefied natural gas, where the economic output flow is given in tonnes transported goods per km.

The complete derivation of the transportation in tonnes per km, and unit processes included, are given in Appendix 10.1.3, Table 10.1.12.

To calculate the weight transported over the loaded and ballast transit, equation 5.2.1 is applied.

$$T = d\sum_{i=1}^{D} V \times (1-r)^{i} \tag{5.2.1}$$

Where:

T =Total goods transported over transit voyage [ktm]

V = Starting volume of transported LNG [m^3]

r = boil-off rate [%]

d = daily covered distance [km]

D = number of days per transit voyage

i = day

The BOG generated over the voyage can be calculated by developing Equation 5.2.1 to Equation 5.2.2:

$$BOG_{total} = \sum_{i=1}^{D} V \times \left[(1-r)^{i-1} - (1-r)^{i}\right] \tag{5.2.2}$$

The covered distance per day is calculated by assuming an average speed of 15 knots. The transit time will in the LCI calculation be rounded up to the closest number of days, and the daily covered distance will be calculated from this. Equation 5.2.1 is also used to derive the amount of BOG emitted during the voyage.

In the case of the container ship, it is assumed that the LNG will be transported directly from Melkøya to Napoli, Italy. The ship will also be refueled in Shanghai, China. An equal LNG plant and transportation distance is assumed. This is done to simplify the calculation and easier distinct the environmental impact potential of the production and bunkering-phase of LNG. For the RoPax ferry, a transportation distance from Hammerfest, Norway to Malmö, Sweden has been applied. Data on the transporting routes are presented in Table 5.2.2.

Table 5.2.2: Fuel transportation distance, LNG

Route	Distance	Sea transit time
Hammerfest - Malmö	2,376km	3d 14h
Hammerfest-Napoli	6,684km	10d

An important note to this is that the LNG plant at Melkøya can be assumed to have a better environmental performance than plants in other countries due to strict national regulations. E.g. the electricity mix used in Norway is close to exclusively produced by hydropower, far from being the case for other countries. This will be further discussed in Chapter 6.

The complete LCI for LNG production and distribution is presented Appendix D.

5.2.4 SYNGAS PRODUCTION

The following section will present the inventory data derived for the processes included upstream to production of synthetic gas, and the gasification itself. The syngas will be used in the methanol synthesis, which will be presented in the next section together with the distribution of the fuel. The life cycle chain of the BTL-fuel is illustrated in Figure 5.2.5. The dotted line indicates the inventory presented in this section. The conditioning of the syngas and removal of inert gases are included in the fuel production-process.

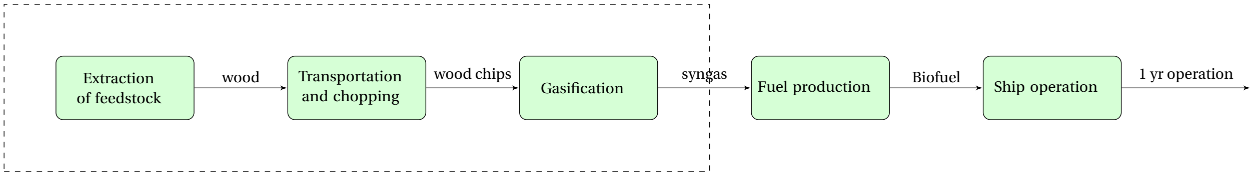

Figure 5.2.5: Life cycle chain of BTL fuels

The feedstock used for the syngas production is set to surplus growth from Norwegian forest, logging and processing residues. The inventory data upstream to the biomass refinery is based on the *Life cycle assessment of second-generation bio-ethanols produced from Scandinavian boreal forest resources: A regional analysis for Middle-Norway*, by Bright and Strømman (2009). The forest biomass (F) and the logging residue (LR) are extracted from the forest, while the process residue (SR) is bought from a regional sawmill. The processes upstream to the gasification process, is illustrated by a simplified flow diagram in Figure 5.2.6. The environmental impact of the forestry operation is allocated among the three biomasses by their economic value.

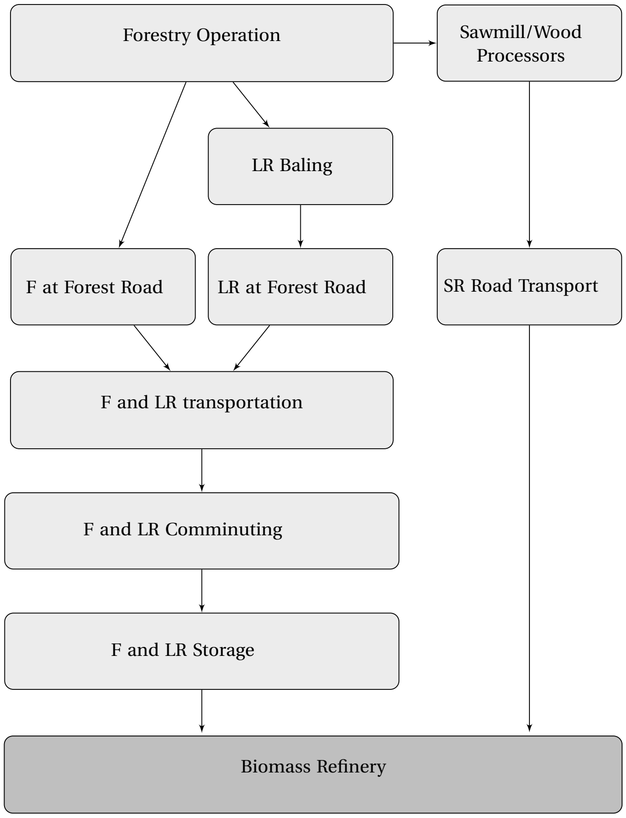

Figure 5.2.6: Simplified flow diagram, feedstock syngas, Bright and Strømman (2009)

It is assumed that the biomass from forest and logging residue are transported 120 km to the biorefinery, where it is comminuted before storage. The wood is chopped by a stationary electric chopper. The moisture mass to dry mass ratio, u, is around 70% after comminuting. Before entering the gasification process, the fresh, chopped wood is stored until the u-ratio is reduced to 55%. The mass content of the chopped wood is 83.1% forest biomass and 16.9% logging residue. The process residue is transported 2km from the sawmill to the biorefinery, where it is directly entered into the gasification process at a u-ratio of 40%.

Emissions from related to biomass loss during storage are included. The study by Bright and Strømman (2009) includes CH_4 and N_2O emissions based on the original carbon and nitrogen contents contained in the wood. A dry material loss of 15.6% is assumed. The dry matter composition of the Norwegian source is used as a proxy for all wood types, which has a carbon content of 50% and a nitrogen content of 5%. The calculation of the emission factors is presented in Appendix 10.1.4

This study's assessment of the biomethanol-production is in large extent based on the Ecoinvent 2.2 report on Bioenergy, Jungbluth et al. (2007a). The processes and flows included will be modified to the study's scope where it is possible and found appropriate. This section will present the inventory data for the syngas production, which will be used in the production of the biofuels assessed.

The biomass refinery facility and operation are based on the LCI of *Synthetic gas, from wood, at fluidized bed gasifier*, Jungbluth et al. (2007a). The modifications made are comprising source of electricity and input of biomass. The transport-processes are excluded, as this has already been accounted for in the upstream processes. Transportation from the storage to the syngas plant is excluded, as it is assumed that the storage is located at the biorefinery.

The choice of gasification technology is based on the fact that fluidized bed gasification is considered as more fuel-flexible compared to fixed bed gasifiers, with regard to size and biomass composition. Fluidized bed gasifiers are also more adapted to larger capacities, Jungbluth et al. (2007a).

At the gasification plant the chipped waste wood is utilized to produce syngas. The Ecoinvent unit process *synthetic gas, from wood, at fluidized bed gasifier* considers the production of 1 Nm^3 of syngas by gasification of mixed wood chips. The process includes the following production stages:

- drying of wood chips (down to 10-15% moisture)
- comminution of wood chips (down to a size of 30x30x30 mm)
- fluidized bed gasification of the chips
- syngas treatment (removal of impurities and contaminants)

The overall energy efficiency of the process is 53.1%.

To reach the desired moisture level of the biomass for the gasification process, the biomass has to be dried, requiring electricity and heat. By knowing the moisture ratio and density characteristics of the different biomass it is possible to calculate the amount of water that must be removed from the biomass in the gasification process as well as the electricity required in the drying process. This can be done by Equation 5.2.3.

$$Electricity = Bio_{u=f} - Bio_{u=m} \times e \tag{5.2.3}$$

Where:

Bio = Amount of biomass[kg]
f = moisture level at fresh biomass [%]
m = ideal moisture ratio, u=15%
e = Electricity consumed per kg water removed, = 0.025kWh/kg.

The amount of electricity consumed per amount of water removed is taken from the Ecoinvent Bioenergy report.

The syngas density is equal to 1.15kg Nm^3. 2.445 kg of syngas per dried kg wood chips are set in order to calculate the amount of wood required in the production. The amount of biomass from storage consumed per Nm^3 of Syngas is calculated by Equation 5.2.4.

$$Biomass_{u=f,i} = \frac{\Delta Biomass_{u=m}}{1+m} \times \frac{AP}{BU} \tag{5.2.4}$$

Where:

Bio =Amount of biomass[kg]

i = type of biomass

f = moisture level at fresh biomass [%]

Δ = share of total biomass used [%]

m = ideal moisture ratio, u=15%

AP = Apperent density [kg/m^3]

BU = Bulk density [kg/m^3]

As in the Ecoinvent report of syngas production, it is assumed that the heat consumed in addition electricity, is supplied by combustion of cleaned syngas. This increases the gross production of syngas to 1.582 Nm^3; where $1Nm^3$ is the net production and 0.582 Nm^3 is used in the gasification process.

The characteristics of the woodchips used are given in Table 5.2.3.

Table 5.2.3: Feedstock characteristics, Scandinavian wood

Source	Apparent density kg/ m^3	Bulk density kg/m^3dry	U at harvest %	U after storage 0.55
forest, logging residue	399	188.6	70	55
Process residues	364	188.6	40	-

5.2.5 METHANOL PRODUCTION AND DISTRIBUTION

It is assumed that methanol synthesis is occurring at the same refinery in which the syngas is produced.

The methanol synthesis is modeled using Ecoinvent's unit process data of *methanol, from synthetic gas, at plant*. Adjustment of the inventory data includes changing electricity source to Norwegian production mix, and elimination of transportation from syngas facility to methanol plant. It is assumed that all the sulfur has been removed from the syngas, making the methanol a sulfur-free fuel.

It should be mentioned that the syngas production plant and methanol plant is not integrated in terms of construction related processes and energy use. Significant energy savings can be realized through optimizing a coordinated plant. Energy produced by the methanol synthesis may for example be reused for drying of raw biomass material. This will be further discussed in theLife Cycle Interpretation, Chapter 7.

A *transoceanic freight ship* is taken from the Ecoinvent database to represent the tanker which transport the methanol to the bunkering port for the vessels assessed in the study. It is assumed that the freight ship runs on heavy fuel oil from a regional storage. The distance used in the inventory is modeled from Trondheim, Norway to Malmö, Sweden.

Since the use of biofuels in container ships is not considered as realistic in any near future, and in order to simplify the model, the same production and transportation processes have been used for the container ship. Emissions related to refueling and storage is not included.

The life cycle of methanol is presented in the simplified flow diagram in Figure 5.2.7. The process of *Feedstock extraction and processing* was described in the previous section.

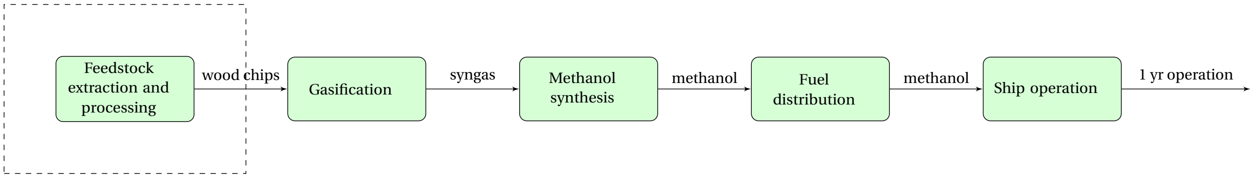

Figure 5.2.7: Life cycle chain of methanol

The complete LCI for Methanol production and distribution is presented in Appendix D.

5.2.6 DME PRODUCTION AND DISTRIBUTION

The life cycle inventory of the DME, produced by gasification of black liquor, is modeled based on the LCA study by Jungbluth et al. (2007b), which will also be referred to as the RENEW project. No modifications have been made to the production inventory. The refinery modeled is based on the running Chemrec black liquor gasification plant at Domsjö, Sweden. The inventory is based on its production level at the time the data was collected (year 2006).

On January 26, 2011, the European Commission approved an aid of €55 million to Sweden and the Domsjö research and development (RD) project in order to *develop a demonstration plant for the production of bio-methanol and other biofuels from pulp mill residue material...* and *...replace traditional fuel in the transport sector, thereby limiting Europe's dependency on fossil fuel and reducing carbon dioxide emissions*, Europa (2011). Building on existing industrial infrastructure Chemrec transforms pulp and paper mills into biorefineries producing DME, Methanol and FT-diesel with black liquor gasification technology.

The black liquor is initially used in recovery boilers to produce steam and for power production for the pump mill. It is in this case assumed that the energy feedstock is replaced by biomass, making the plant self-sufficient. No direct external electricity or other non-renewable energy supply is considered in the modeled process. The integration of the gasification plant with the pulp mill is illustrated in Figure 5.2.8.

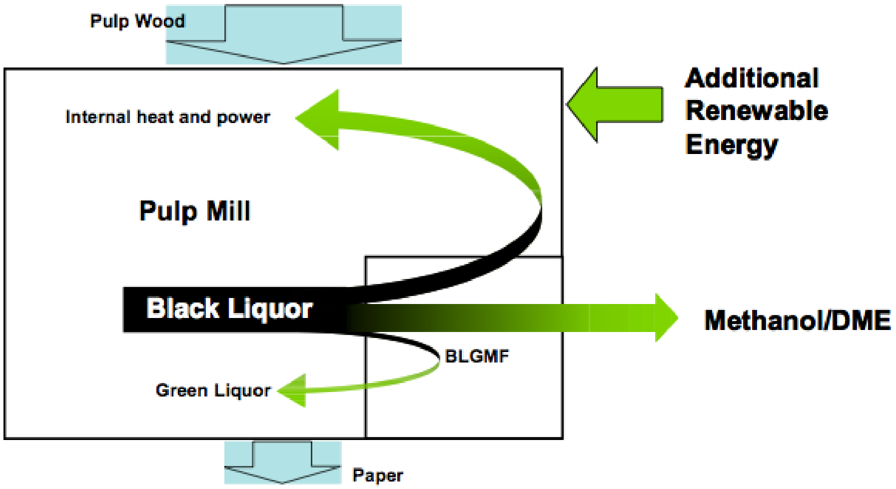

Figure 5.2.8: Illustration of process integration of black liquor gasification with pulp and paper mill

The black liquor is gasified with oxygen in a refactor-lined entrained flow reactor. The result is smelt droplets consisting of inorganic compounds and an energy-rich syngas, which is separated in a quench dissolver. The syngas is scrubbed, cooled and cleaned before it enters the methanol/DME synthesis process.

Key figures of the black liquor conversion process are presented in Table 5.2.4. The ratio biomass to liquid is given in terms of energy and hydrogen input.

The feedstock applied in the LCA study is short rotation wood of the type willow-salix. This is an soft wooded, agricultural product, which is cultivated over a period of several years, and is harvested in bundles. The rotation time depends on growing conditions, and ranges from 3-5 years.

The inventory for the biomass production/resource extraction is described as follows: *The processes of soil cultivation, sowing, weed control, fertilization, pest and pathogen control, harvest and balling. Machine infrastructure and a shed for machine sheltering is included. Inputs of fertilizers, pesticides and planting stocks as well as their transports to the farm are considered. The direct emissions on the field are also included. The system boundary is the field*, Jungbluth et al. (2007b).

Table 5.2.4: Key figures of the black-liquor conversion process

Process	Entrained flow gasification of black liquor for DME production
Biomass	Wood, willow-salix
Product	BTL-DME
Developer	CHEMREC
Conversion rate (biomass to all liquids)	69%
Capacity biomass input [MW]	500
All liquid products [t/h]	29.0

Table 5.2.5: Feedstock characteristics, Willow-salix

Source	Apparent density kg/ m^3	Bulk density kg/m^3dry	U at harvest %	LHV (dry matter) MJ/kg
Willow salix	285-571	200-400	30	18.8

The biomass preparation process includes the following inputs: Biomass, machinery, fuels, electricity, further consumables, storage facilities, transport services, waste management services. Stressors associated with the processes that are included are land occupation, emissions to air and water from fuel combustion. Biomass loss related to storage has been included. It is here assumed a biomass loss during storage of 7%. The emissions are modeled as biogenic CO_2 emissions calculated based on the carbon content of the lost biomass. The carbon content is set to 48%. Release of heat to the environment has also been included. The calculation of the emission factors related to biomass storage is presented in Appendix 10.3.

The biomass is dried at the storage before transported to the conversion plant. The water content of the biomass is approximately 15-20% when it enters the gasification process. The total amount of wood consumed corresponds to the replacement of black liquor and the wood required by the power plant for producing heat and electricity.

As in the report by Jungbluth et al. (2007b), it is applied an average one-way transport distance of biomass (wood) to the pulp mill and conversion plant is estimated with 150km by truck (50% load, class 32t).

The inventory for the fuel synthesis plant includes: Land occupation and transformation, buildings, chemical facilities. The feedstock is gasified over a zinc catalyst. Pure zinc has been used as a proxy in the catalyst inventory, which is based on literature.

Data on the emission profile from the conversion processes are rarely available. The emissions occur during the gas cleaning, and mainly consist of biogenic CO_2 and N_2. The emission inventory taken from Jungbluth et al. (2007b) is based on literature, and has been assessed based on emission profiles from modern gas power plants and additional information provided by Chemrec. In case of shut-down of the operation or malfunctioning of certain installations, it is assumed that the unused syngas will be burned in flare.

The unit process *transoceanic freight ship* is taken from the Ecoinvent database to represent the tanker which transport the DME from the biorefinery to the bunkering port. It is assumed that the freight ship runs on heavy fuel oil from a regional storage. The distance used in the inventory is modeled from actual location of the plant, to Malmö, Sweden.

Since the use of biofuels in container ships is considered as not realistic in any near future, and in order to simplify the model, the same production and transportation processes have been used for the container ship. Emissions related to refueling and fuel-storage are not included.

The DME system can be illustrated by the flow diagram in Figure 5.2.9. The flow diagram illustrates the connection between the foreground processes. The complete LCI for DME production and distribution is presented in Appendix D.

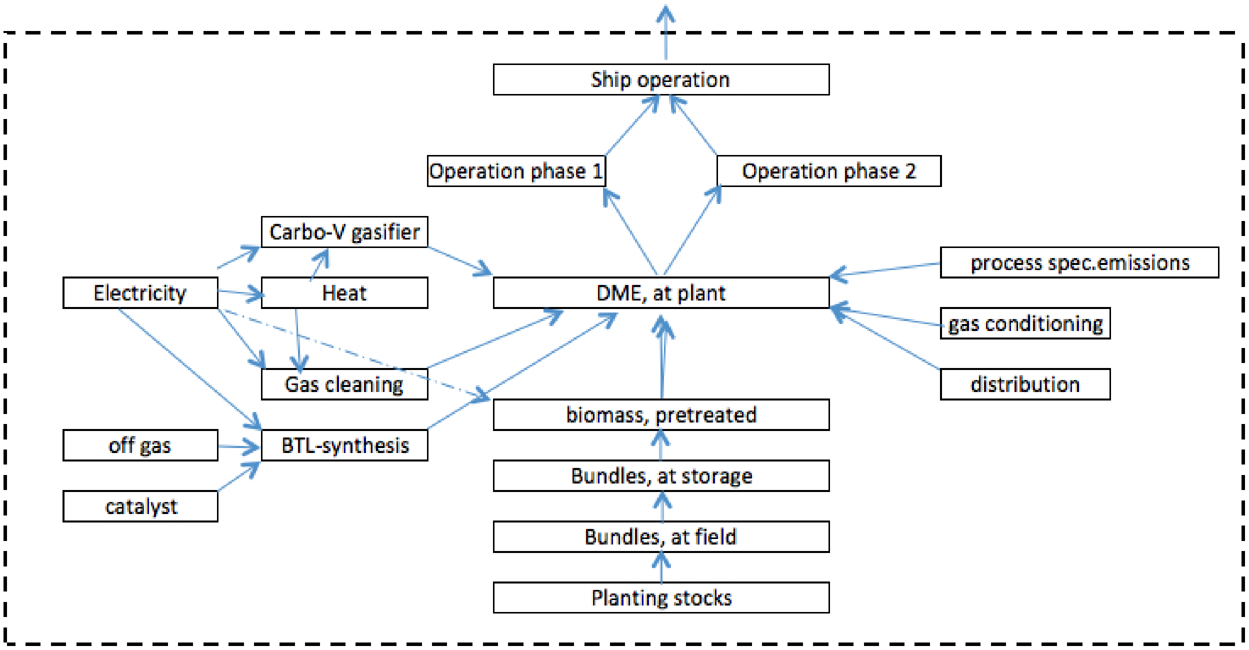

Figure 5.2.9: Flow diagram, DME foreground system

5.2.7 FISCHER-TROPSCH DIESEL PRODUCTION AND DISTRIBUTION

The life cycle inventory data of the FT-diesel production is modeled based on the LCA study by Jungbluth et al. (2007b). The technology applied is centralized entrained flow gasification of short-rotational wood. The choice of technology is based on the completeness of the provided LCI and the high BTL-conversion rate.

Key figures of the conversion process are presented in Table 5.2.6. The ratio biomass to liquid is given in terms of energy and hydrogen input.

Table 5.2.6: Key figures of the FT-diesel conversion process

Process	Centrilized entrained flow gasification
Product	BTL-FT
Biomass	Wood, willow-salix
Developer	CUTEC
Conversion rate (biomass to all liquids)	53%
Capacity biomass input [MW]	499
All liquid products [t/h]	22.5

The syngas is produced by the Carbo-V process, which is illustrated by Figure 5.2.10.

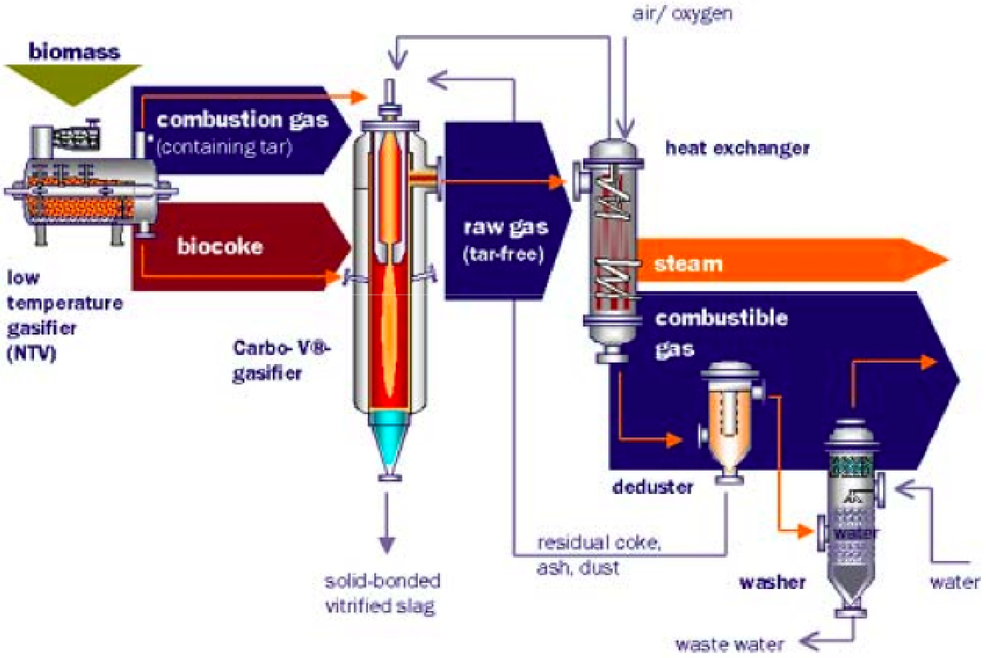

Figure 5.2.10: Flow chart of the Carbo-V process, Jungbluth et al. (2007b)

In the first stage of the conversion process is carbonizing of the dried biomass, using a specially developed low temperature gasifier to produce biocoke and low temperature carbonization gas. The low temperature carbonized gas is then oxidized into CO, H_2, CO_2 and steam in the combustion chamber of a Carbo-V gasifier, where the temperatures are ranging between 1,300°C and 1,500°C. The final and third step is the biocoke from the low temperature gasifier blown into the Carbo-V reactor below the combustion chamber. Here the biocoke reacts with the gas from the combustion chamber. The reactions are endothermic, making the temperature of the gas drop from 1,300°C to 800°C.

Many of the processes modeled for the DME-production by Jungbluth et al. (2007b) are assumed identical to the FT-diesel production. This includes plant construction, feedstock supply-chain, off-gas, catalyst, electricity and heat production. In addition is the distribution process modeled as for the DME-distribution, see Section 5.2.6.

Unfortunately, the inventory data for the waste management processes have not been included in the public RENEW report, due to confidentiality reasons. Where similar unit process was not available in the Ecoinvent 2.2 Database, the process has been excluded. It is assumed that the waste management processes will not notably influence the functional unit's impact potential.

The FT-diesel system can be illustrated by the flow diagram in Figure 5.2.11. The flow diagram illustrates the connection between the foreground processes.

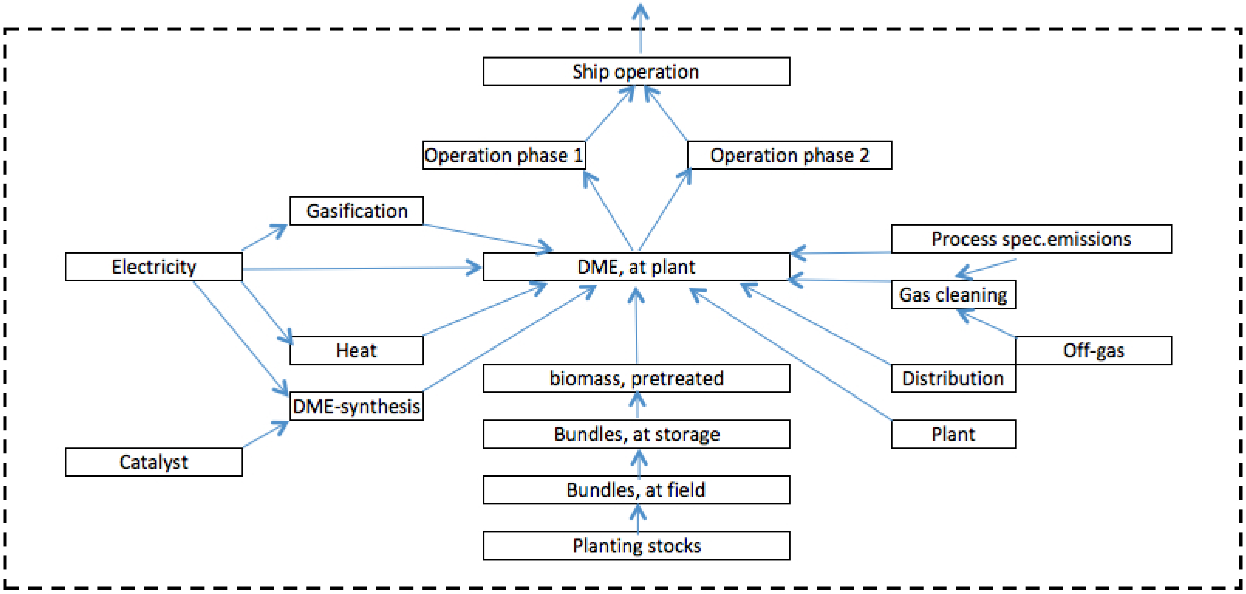

Figure 5.2.11: Flow diagram, FT-diesel foreground system

The complete LCI for FT-diesel production and distribution is presented in Appendix D.

5.3 OPERATIONAL PROFILE

5.3.1 ROPAX FERRY

A RoPax-ferry is a vessel built for freight vehicle transport along with passenger accommodation. The RoPax-ferry considered in the study is running on three engines of 2 MW each. One additional engine is not used in normal operation, but can be used in emergencies, or when other engines are being maintained. The ferry is operating in a limited geographical area, in this study specified as the Baltic Sea. The ferry makes 20 trips a day, and has in average 254 operating days during a year. For each trip, the ferry spends 45 minutes on transit and 15 minutes in port. The typical annual operating profile for the small ferry is given in Table 5.3.1.

Table 5.3.1: Annual operating profile, RoPax ferry

operational-phase	Main engine load [%]	Duration [hours]	Propulsion [kW]	Hotel Loads [1] [kW]
Transit	80%	3810	4500	1000
In Port	30%	1270	-	1000

It is assumed that the RoPax ferry is able to run on all the alternative fuels, without any significant modifications of the ship construction and engines.

5.3.2 CONTAINER SHIP

As earlier described in Section 1.3.1, the 4,500 TEU container ship analyzed in this study sails from Europe to East Asia 6 times a year. The ports used are Napoli, Italy and Shanghai, China. The distance covered is about 8,500 NM in each direction, and its typical annual operating profile for the container ship is given i Table 5.3.2.

Table 5.3.2: Annual operating profile, container ship

operational-phase	Main engine load [%]	Duration [hours]	Propulsion [kW]	Hotel Load [1] [kW]
High speed transit	80%	985	31059	3060
Normal speed	70%	2430	23751	3060
Ballast transit	60%	2497	16443	1530
Maneuvering	30%	657	12789	3130

It was mentioned in Section 2.5 that GHG emissions can be reduced by shipping at lower speeds. Shipping at lower speed will in theory increase the amount of ships in operation in order to maintain the transferring capacity. Due to the financial crisis in 2008, the fear of increased impacts from ship building might be overestimated. The financial crisis rested in an overcapacity in the fleet, which has slowed down the ship building industry. The current overcapacity is also giving ship-owners an incentive to reduce the speed, in order to get more ship in operation.

This incentive and the fact that the environmental impacts of a possible increased shipbuilding are minor compared to the reduced fuel consumption. These are the reasons why this thesis will adjust the typical operational profile of the large container ship, excluding the high speed interval by increasing the time spent on the normal speed and ballast transit interval. The original operational profile is given in Table 5.3.2.

To be able to transfer the time travelled with high speed to the normal and ballast speed interval, the definition of the Admiralty coefficient, A, is used. The constant is valid for a given hull and gives the approximate relationship between the needed propulsion power P, ship speed v, and displacement $\bigtriangledown$, given by equation 5.3.1, MAN (2011).

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[1] The term hotel load is used with respect to ships to describe their non-propulsion energy requirements, e.g. lights, air conditioning, computers, water purifiers, radios, etc.

$$A = \frac{\nabla^{2/3} v^3}{P} \tag{5.3.1}$$

By setting A equal for the two operational profiles, i.e. high speed (hs) and normal speed (ns), one obtain the Equation 5.3.2. An expression of the change in speed can then be derived as presented in Equation 5.3.3.

$$\frac{\nabla^{2/3} v_{hs}^3}{P_{hs}} = \frac{\nabla^{2/3} v_{ns}^3}{P_{ns}} \tag{5.3.2}$$

$$\frac{v_{hs}}{v_{ns}} = \sqrt[3]{\frac{P_{hs}}{P_{ns}}} \tag{5.3.3}$$

The advantage of using this derivation is that given the propulsion powers and time spent with high speed, the corresponding normal speed duration can be calculated without defining the associated speeds.

5.4 ENGINE EFFICIENCY

A dual-engine has been used in this study because a variety of fuels can be applied to the engine, i.e. HFO, MDO, LNG, FT-diesel, and methanol. Currently, there exists only one container ships using dual engine to the authors knowledge, Chew (2013), but it is expected that the LNG becomes more relevant as fuel for these ships, low speed dual engines will be seen on these ships. The engine producer MAN has received its first order for a 25MW, 2-stroke dual fuel engine that will be used in a 3,100 TEU container ship, Chryssiakis (2013). Statistics from 100,000 vessels in 2010 indicated that 99% of the fleet is powered by diesel engines, Trozzi et al. (2009).

Diesel engines are often categorized by their rotational speeds, measured by revolutions per minute (rpm), into three unofficial groups:

1. High-speed engines (> 1,000 rpm)
2. medium-speed engines (300 - 1,000 rpm)
3. slow-speed engines (< 300 rpm)

High- and medium-speed engines are predominantly four-stroke engines, while the slow speed engines are of the two-stroke type. Slow speed engines are the largest diesel engines, and are primarily used to power ships.

Statistics for container ships show that in 2010 92.98 % of the installed main engine power was of the slow speed diesel type (SSD) using HFO as fuel, Trozzi and Vaccaro (2010). The statistics gives no data for RoPax ferries, but based on the data for RoRo-vessels, medium speed diesel engines are the most used type of engine. The engines categories used in this study is a low speed dual engine for the container ship, and a medium speed dual engine for the RoPax ferry.

Table 5.4.1 presents the engine efficiencies for a medium speed Wärtsilä dual fuel engine, given different operational stages. Data on fuel consumption has been obtained through direct measurements in steady-state engine operation under different main engine loads. The engine efficiencies presented in the table has been calculated using the lower heating values of HFO and LNG, given in Table 2.7.1, and by extrapolation in order to match the operational profiles in the study.

It is expected that the engine efficiency will be higher for a low-speed engine. When comparing different low- and medium speed engines produced by Wärtsilä, the Brake specific fuel consumption (BSFC) seem to decrease around 10% using low speed engines, Wärtsilä (2013). It is followed that the engine efficiencies given in Table 5.4.1 are increased by 10% for the low speed dual engine used by the container ship in this study.

Table 5.4.1: Engine efficiency, medium-speed dual engine

operational-phase	Main engine load [%]	Diesel mode [%]	Gas mode [%]
High speed transit	80%	47.0	48.0
Normal speed	70%	45.7	45.6
Ballast transit	60%	44.3	43.1
Maneuvering	30%	36.4	33.6

5.5 EMISSION FACTORS

The emission factor (EF) - amount of emission emitted for unit energy consumption during combustion - varies for the different fuels. Where emission factors for the different engine loads have been available, this has been used. In lack of specific data, an average emission factor has been used. Where possible emission measurements from engine measurements have been applied, other emission factors are taken directly from literature, or has been assumed on the basis of relative literature.

5.5.1 EMISSION FACTORS OF CONVENTIONAL MARINE FUELS

The emission factors used for CO_2, NO_X, CO, are based on direct measurements of the medium speed Wärtsilä dual fuel engine. It is assumed that the NO_X emission factors will be increased by 10% for the low-speed engine used in the container ship, Chryssiakis (2013). The emission factors measured in diesel mode are presented in Table 5.5.1. The emission factors are given in grams emitted pollutant per kWh propulsion output.

Table 5.5.1: Measured emission factors, medium-speed dual engine, diesel mode

Fuel mode	Operational-phase	Main engine load [%]	NO_X [g/kWh]	CO_2 [g/kWh]	CO [g/kWh]
Diesel mode	High speed transit	80%	11.55	569.96	0.481
	Normal speed	70%	12.05	588.04	0.519
	Ballast transit	60%	12.55	606.12	0.558
	Maneuvering	30%	15.23	720.24	1.056

Based on the temporal scope given in Section 1.3.2, Tier II is used in this study as the decisive regulation for both vessels. As given in Table 2.3.2, the NO_X limit applied to ships with a rpm $130 \leq n < 2000$ built in or after 2011, is given by Equation 5.5.1:

$$44 \times n^{-0.23} \tag{5.5.1}$$

The rated speed for the medium speed engine is 750 rpm, which results in a NO_X limit of 9.60g/kWh. For engines with a rated propulsion speed lower than 130 rpm, 130 rpm is used in Equation 5.5.1 to calculate the emission limit. For the low speed with a rpm less than 130, 14.36g/kWh is the upper limit.

As seen in 5.5.1 and illustrated in Figure 5.5.1 , the measured NO_X emission factors for diesel mode exceed the Tier II limit for the medium speed engine (rpm = 750), and for the low speed engine (rpm = 100) for low engine loads. It is here assumed that abatement technologies are applied to reduce the upper emission factor down to the required level for the medium speed engine. It is further assumed that the relationship between emission factors and engine load remains. It is however found most likely that even with a 10% increase of emissions, the weighted average of NO_X emissions for the low speed engine will comply with the Tier II limit, and no lowering of the emission profile is therefore made for this engine.

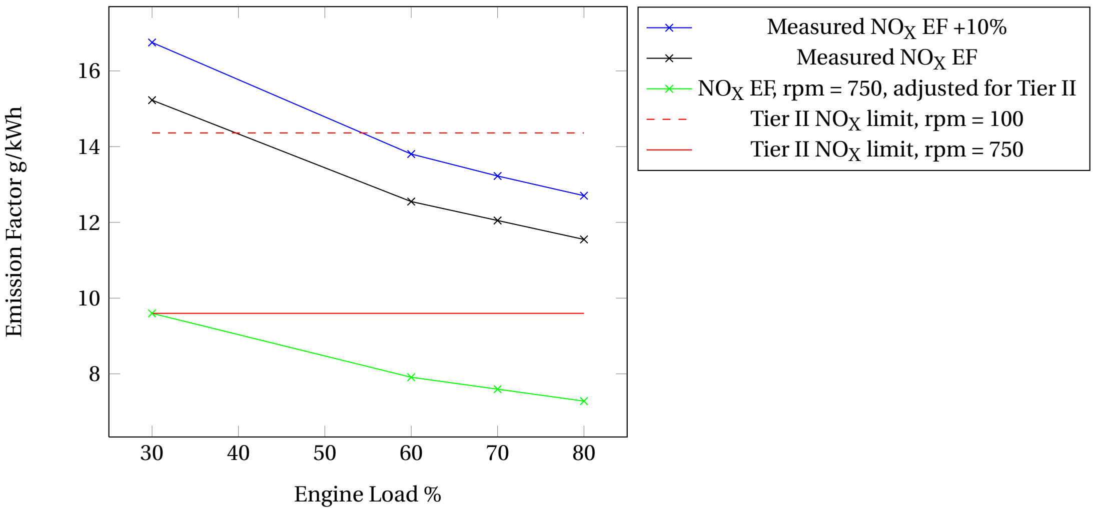

Figure 5.5.1: NO_X-emission factors, measured and applied

Where direct measurements have not been available, the remaining emission factors are based on literature. The EMEP/EEA emission inventory guidebook from 2009, by Trozzi et al. (2009), provides emission factors for NMVOC and PM given operational phase and engine type. The emission factors for HFO and MDO/MGO are presented in Table 5.5.2, and are given in kg pollutant per tonnes of fuel consumed in order to make it compliant with the varying engine efficiencies measured. Emission factors from Trozzi et al. (2009) that are not specified by engine type or operational phase is given in Table 5.5.3.

Table 5.5.2: Emission factors for NMVOC, $PM_{2.5}$ and PM_{10} for different fuel/engine types

Operational-phase	Engine type	Fuel [kg/tonne]	NMVOC [kg/tonne]	$PM_{2.5}$, PM_{10} [kg/tonne]
Normal speed	Medium speed engine	HFO	2.3	3.8
		MDO/MGO	2.4	1.5
	Slow speed engine	HFO	3.0	8.7
		MDO/MGO	3.2	1.6
Maneuvering/hotelling	Medium speed engine	HFO	6.3	10.3
		MDO/MGO	6.6	4.0
	Slow speed engine	HFO	8.2	11.2
		MDO/MGO	8.6	4.4

The sulfur content of the conventional fuels are specified in Table 5.5.4. The sulfur content of the HFO is set after the Marpol Annex VI regulations earlier presented in Table 2.3.1. It is assumed that the MDO/MGO used by the container ship will have a lower sulfur content compared to the HFO. But as low-sulfur fuels are more expensive, no drastic reduction in sulfur content is applied. For the RoPax ferry operating the ECA however, a low sulfur content is chosen for the MDO/MGO. A sulfur content of 0.1% corresponds to the regulations applied on and after 1st of January 2015 inside the ECA. It must be noted that the values applied for MDO/MGO go beyond imposed regulations.

Unlike nitrogen oxides, it is not possible to enter sulfur oxides as an emissions in the inventory data by the Ecoinvent 2.2 database, where the emissions have to be allocated between SO, SO_2 and and SO_3. The sulfur oxides emissions in this study have been modeled as SO_2 emissions. This is done on the basis of the ReCiPe 2008 impact assessment method, which gives SO, SO_2 and SO_X with the same characterization factor for various impact categories, including Particulate Matter Formation, while it does not include the impact of SO_3.

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[2] *S* is the percentage sulfur content in the fuel.

Table 5.5.3: Default emission factors for ships using HFO or MDO/MGO

Pollutant	HFO	MDO/MGO	Unit
SO_X	$20 \times S^2$	$20 \times S$	kg/tonne fuel
Pb	0.18	0.13	g/tonne fuel
Cd	0.02	0.01	g/tonne fuel
Hg	0.02	0.03	g/tonne fuel
As	0.68	0.04	g/tonne fuel
Cr	0.72	0.05	g/tonne fuel
Cu	1.25	0.88	g/tonne fuel
Ni	32	1	g/tonne fuel
Se	0.21	0.10	g/tonne fuel
Zn	1.20	1.20	g/tonne fuel
HCB	0.14	0.08	mg/tonne fuel
PCB	0.57	0.38	mg/tonne fuel

Table 5.5.4: Applied sulfur content for conventional fuels

Vessel	HFO [%]	MDO/MGO [%]
RoPax ferry	1.0	0.1
Container ship	3.5	2.0

Default emission factors for methane and nitrous oxides are given by Eggleston et al. (2006), and presented in Table 5.5.5. The values are highly uncertain, and are default values derived for diesel engines using heavy fuel oil. The combined factors are used both engine types, and for both HFO and MDO/MGO in lack of accurate data.

Table 5.5.5: Default emission factors for CH_4 and N_2O for ships using HFO or MDO/MGO, Eggleston et al. (2006)

Pollutant	HFO	Unit
CH_4	0.05	kg/tonne fuel
N_2O	0.08	kg/tonne fuel

5.5.2 EMISSION FACTORS OF LNG

The emission factors used for CO_2, NO_X, CO, are based on direct measurements of the medium speed Wärtsilä dual fuel engine. It is assumed that the NO_X emission factors will be increased by 10% for the low-speed engine used in the container ship, Chryssiakis (2013). The emission factors measured in diesel mode are presented in Table 5.5.6. The emission factors are given in grams emitted pollutant per kWh propulsion output. As for the diesel mode, it is assumed that the NO_X emission factors will be increased by 10% for the low-speed engine used in the container ship, Chryssiakis (2013).

It is assumed that there will be a leakage of methane gas from the engine in gas mode, equal to 1% of the CO_2 direct emissions in gas mode, Chryssiakis (2013). In lack of measurement data, the additional emission factors are taken from literature, Verbeek et al. (2011). The emission factor of particulate matter is given in $PM_{2.5}$ and PM_{10} in correspondence with the EEA emission inventory guidebook, Trozzi et al. (2009). The emission factors applied for LNG combustion are presented in Table 5.5.7. NMVOC is considered negligible, Verbeek et al. (2011).

There has been no adjustments for boil-off-gas for the ship operation. Possible BOG formation in the fuel storage tanks is assumed being fully utilized during combustion.

Table 5.5.6: Measured emission factors, medium-speed dual engine, gas mode

Fuel mode	Operational-phase	Main engine load [%]	NO_X [g/kWh]	CO_2 [g/kWh]	CO [g/kWh]
Gas mode	High speed transit	80%	1.119	387.89	1.808
	Normal speed	70%	1.235	405.19	2.654
	Ballast transit	60%	1.350	422.5	3.500
	Maneuvering	30%	2.350	507.05	7.320

Table 5.5.7: Default emission factors for CH_4 and N_2O for ships using LNG, Verbeek et al. (2011)

Pollutant	LNG	Unit
$PM_{2.5,10}$	0.05	g/kWh
N_2O	0.00134	g/MJ

5.5.3 EMISSION FACTORS OF BIOFUELS

Very few measurements of emission factors using alternative fuels in marine engines have been published. The two publications referred to in Section 3.5 also consider different engines and reference fuels, making it challenging to apply it to this study's base cases.

The biogenic CO_2 emissions from combustion is calculated based on the carbon content of the fuel, given in Table 2.7.1. It is assumed that the full carbon content of the fuel is emitted as CO_2. The assumption is made based on the low CO proportion measured, see Table 5.5.1 and Table 5.5.6, and the characterization factors of CO related to the assessed impact categories, see Section 6.2. Direct emissions of NMVOC and CH_4 are not included.

The assumptions of non carbon-emission factors related to combustion of biofuels have been made based on the available literature on marine engines using biofuels, and Chryssiakis (2013). The relative changes compared to HFO emissions, at diesel mode for the respective engine, are presented in Table 5.5.8.

Table 5.5.8: Assumed non-carbon emission factors for biofuels, relative to the respective HFO emissions

Pollutant	Methanol	DME	FT-diesel
NO_X	-30%	-55%	-10%
SO_X	-100%	-100%	-100%
$PM_{2.5,10}$	-95%	-95%	-95%

6

LIFE CYCLE IMPACT ASSESSMENT

6.1 INTRODUCTION

In this chapter the results from the Life Cycle Inventory are processed and presented by 18 midpoint impact categories, defined in Table 6.1.1. The results from the LCI are characterized using the ReCiPe hierarchist impact assessment method, earlier described in Section 4.2. The method of the Life Cycle Impact Assessment is briefly described in Chapter 4.

The Life Cycle Impact Assessment will focus on three key impact categories. The relative share of impacts related to well-to-tank and tank-to-propeller processes will be presented. Key findings from the contribution analysis for each system will be presented and the complete results are to be found in Appendix D. HFO will be used to as the reference fuel in comparisons where nothing else is specified.

Table 6.1.1: ReCiPe hierarchist impact categories

Impact Category	Unit	Char. Factor	Scale
Agricultural Land Occupation	m^2yr (agricultural land)	ALOP	Global, regional, local
Climate Change	kg (CO_2 to air)	GWP	Global
Fossil Fuel Depletion	kg (crude oil, 42 MJ/kg)	FDP	Global, regional, local
Freshwater Ecotoxicity	kg (14DCB to freshwater)	FETP	Local
Freshwater Eutrophication	kg (P to freshwater)	FEP	Local
Human Toxicity	kg (14DCB to urban air)	HTP	Global, regional, local
Ionising Radiation	kg (U_{235} to air)	IRP	Local
Marine Ecotoxicity	kg (14-DCB7 to marine water)	METP	Local
Marine Eutrophication	kg (N to freshwater)	MEP	Local
Mineral Resource Depletion	kg (Fe)	MRDP	Global, regional, local
Natural Land Transformation	m^2 (natural land)	NLTP	Global, regional, local
Ozone Depletion	kg (CFC-115 to air)	ODP	Global
Particulate Matter Formation	kg (PM_{10} to air)	PMFP	Global, regional, local
Photochemical Oxidant Formation	kg (NMVOC to air)	POFP	Regional, local
Terrestrial Acidification	kg (SO_2 to air)	TAP	Regional, local
Terrestrial Ecotoxicity	kg (14DCB to industrial soil)	TETP	Local
Urban Land Occupation	m^2yr (urban land)	ULOP	Global, regional, local
Water Depletion	m^3 (water)	WDP	Regional, local

6.2 CHOICE OF IMPACT CATEGORIES

The following three midpoint impact categories will primarily be used in contribution analysis and to evaluate the general performance of the system.

6.2.1 AGRICULTURAL LAND OCCUPATION

As the global population grows, the fight over land-based resources between forestry, infrastructure, and natural ecosystems will become more evident. Because of the scarcity of agricultural land, it is necessary to evaluate different production routes of biomass in order to minimize the impact to ecosystems and occupation of agricultural land.

The biofuels assessed in this study are limited to second-generation biofuels in order to avoid the trade-off discussion between food and fuel production. Is is however important to assess the agricultural land occupation potential (ALOP) of the different production routes included in the study.

ALOP is calculated by the amount of agricultural area occupied (in m^2) and *yr* the time of occupation in years.

6.2.2 CLIMATE CHANGE

Climate change is the impact of anthropogenic activity on the radiative balance of the earth. Human health is sensitive to climate variations, and long-term climate change will have some effect, positive or negative, on the global population health, Goedkoop et al. (2009). Climate change increases the risk of acute events like storms droughts and floods, cyclical changes in precipitation, or long-term changes in temperature and sea levels. IPCC has published reports stating that there is strong evidence that greenhouse gas forcing is the dominant cause of global warming during the past several decades, Solomon (2007). Calculating the Global warming potential (GWP) provides a metric that can be used in abatement strategies to limit anthropogenic climate change.

The ReCiPe midpoint methodology is based on commonly accepted CO_2 equivalency factors published in the IPCC report 2007, Solomon (2007). The time horizon is set to 100 years, which is the most frequently used timeframe. The GWP of any substance expresses the integrated forcing of a pulse (of given small mass) of that substance relative to the integrated forcing of a pulse (of the same mass) of the reference gas over some time horizon, Goedkoop et al. (2009).

The impact category is a key issue of the motivation behind the introduction of alternative marine fuels. The conventional fuels are currently making a significant contribution to the global warming. To evaluate the GWP of the different fuel alternatives are therefore essential for assessing the environmental performance of the fuels.

6.2.3 PARTICULATE MATTER FORMATION

Particulate matter is both causing serious health problems and contributes to a negative radiative forcing. Fine particulate matter with a diameter of less than $10\mu m$ (PM_{10}) are formed in air from emissions of sulfur dioxide (SO_2), ammonia (NH_3), and nitrogen oxides (NO_X) among others, Murray et al. (2006). The World Health Organization is stating that *PM affects more people than any other pollutant*, WHO (2008).

PM has both anthropogenic and natural sources. Although both may contribute significantly to PM levels in the atmosphere, shipping is in some regions a significant source of particulate matter formatting compounds. As the alternative fuels might differ from conventional fuel in terms of resulting SO_X and NO_X emissions, it is found most interesting to see how the particulate matter formation might be reduced by introducing alternative marine fuels.

Particulate matter formation potential (PMFP) is expressed in PM_{10}-equivalents.

6.3 RESULTS

6.3.1 TOTAL ENVIRONMENTAL IMPACT POTENTIAL

Table 6.3.1 summarizes the total environmental impact potentials associated with the yearly operation of the RoPax ferry, which will in this chapter be referred to as the ferry.

The environmental impact potential of Climate Change (GWP), Agricultural Land Depletion (ALOP) and Particulate Matter Formation (PMFP) will be presented in detail for both vessels in the following sections. The environmental impact potential per MJ fuel consumed by the ferry are given in Table 6.3.2 for the three key impact categories.

Table 6.3.1: Total environmental impact potential per functional unit, RoPax ferry

CF	Unit	HFO	MDO/MGO	LNG	Methanol	DME	FT-diesel
ALOP	m^{2}yr	7.78E+03	7.72E+03	8.12E+02	2.48E+08	1.30E+05	1.42E+05
GWP	kg	1.49E+07	1.51E+07	1.38E+07	6.77E+06	2.95E+06	3.32E+06
PMFP	kg	9.36E+04	2.85E+04	8.83E+03	3.93E+04	2.76E+04	4.26E+04
FDP	kg	5.16E+06	5.25E+06	5.41E+06	1.30E+06	6.95E+05	9.32E+05
FETP	kg	1.30E+04	1.28E+04	9.41E+02	5.70E+04	2.37E+04	1.48E+04
FEP	kg	3.98E+02	3.91E+02	2.21E+01	1.02E+03	1.64E+03	1.60E+03
HTP	kg	7.73E+05	4.44E+05	2.47E+04	4.52E+06	2.35E+06	8.14E+05
IRP	kg	2.93E+05	2.86E+05	1.19E+04	6.17E+05	3.08E+05	2.76E+05
METP	kg	3.36E+04	1.65E+04	2.20E+03	4.81E+04	2.98E+04	1.75E+04
MEP	kg	2.25E+04	5.39E+03	3.79E+03	2.27E+04	1.33E+04	2.24E+04
MRDP	kg	5.09E+04	5.21E+04	2.03E+04	2.99E+05	4.14E+05	3.05E+05
NLTP	m^2	7.46E+03	7.60E+03	5.56E+02	1.87E+03	7.58E+02	8.56E+02
ODP	kg	1.87E+00	1.90E+00	4.70E-03	9.38E-01	2.41E-01	3.21E-01
POFP	kg	1.97E+05	5.82E+04	3.52E+04	4.43E+05	1.03E+04	1.74E+05
TAP	kg	1.95E+05	4.77E+04	1.66E+04	9.64E+04	7.10E+04	1.07E+05
TETP	kg	1.63E+03	1.19E+03	9.02E+00	7.16E+02	4.99E+02	3.19E+02
ULOP	m^{2}yr	2.24E+04	2.29E+04	1.07E+03	1.25E+05	5.61E+04	6.28E+04
WDP	m^{2}yr	6.41E+03	6.40E+03	3.38E+02	2.76E+04	4.62E+04	3.43E+04

Table 6.3.2: Total environmental impact potential/MJ, RoPax ferry

CF	Unit	HFO	MDO/MGO	LNG	Methanol	DME	FT-diesel
ALOP	m^{2}yr	4.50E-05	4.46E-05	4.76E-06	1.43E+00	7.54E-04	8.29E-04
GWP	kg	8.59E-02	8.73E-02	8.09E-02	3.91E-02	1.71E-02	1.94E-02
PMFP	kg	5.41E-04	1.65E-04	5.17E-05	2.27E-04	1.59E-04	2.50E-04

Table 6.3.1 shows that by applying biofuels significant reduction of environmental impact potential can be achieved for the following impact categories: Climate Change, Fossil Fuel Depletion, Natural Land Transformation, Ozone Depletion, Particulate Matter Formation, Terrestrial Acidification, and Terrestrial Ecotoxicity.

It can be seen from the results that the use of biofuels results in a higher water depletion potential, compared to fossil fuels. The highest score is related to the use of DME, while the LNG running ferry provides the lowest WDP. Around 15% of the global water consumption is related to energy production, Birol (2012). In order to meet the future demands of energy, efficient use of water is an important step to sustainability.

Other impact categories where the three biofuels have significantly higher impact potential compared to the reference fuel are: Agricultural Land Occupation, Freshwater Eutrophication, Mineral Resource Depletion and Urban Land Occupation. The use of methanol shows in addition a high potential of Freshwater Ecotoxicity and Human Toxicity compared to the other fuels.

Table 6.3.3 summarizes the total environmental impact potential associated with the yearly operation of the large container ship, which will in this chapter be referred to as the container ship.

The environmental impact potential per MJ fuel consumed by the container ship is given in Table 6.3.4 for the three key impact categories.

Table 6.3.3: Total environmental impact potential per functional unit, container ship

CF	Unit	HFO	MDO/MGO	LNG	Methanol	DME	FT-diesel
ALOP	m^{2}yr	4.80E+04	4.76E+04	7.21E+03	1.53E+09	8.29E+05	8.74E+05
GWP	kg	9.96E+07	1.01E+08	1.01E+08	4.18E+07	1.88E+07	2.05E+07
PMFP	kg	1.28E+06	7.70E+05	6.88E+04	4.03E+05	2.79E+05	4.66E+05
FDP	kg	3.18E+07	3.24E+07	3.48E+07	8.01E+06	4.42E+06	5.75E+06
FET	kg	8.03E+04	7.89E+04	7.82E+03	3.52E+05	1.51E+05	9.15E+04
FEP	kg	2.46E+03	2.41E+03	2.48E+02	6.30E+03	1.04E+04	9.88E+03
HTP	kg	4.71E+06	2.81E+06	2.41E+05	2.79E+07	1.49E+07	5.02E+06
IRP	kg	1.81E+06	1.77E+06	1.52E+05	3.81E+06	1.96E+06	1.71E+06
METP	kg	2.05E+05	1.02E+05	1.59E+04	2.97E+05	1.89E+05	1.08E+05
MEP	kg	2.63E+05	2.63E+05	3.13E+04	2.27E+05	1.39E+05	2.49E+05
MRDP	kg	3.14E+05	3.21E+05	1.50E+05	1.85E+06	2.63E+06	1.88E+06
NLTP	m^2	4.60E+04	4.69E+04	3.62E+03	4.82E+03	4.74E+03	5.28E+03
ODP	kg	1.15E+01	1.17E+01	4.20E-02	5.79E+00	1.53E+00	1.98E+00
POFP	kg	2.30E+06	2.25E+06	2.99E+05	3.41E+06	1.08E+06	1.95E+06
TAP	kg	3.02E+06	2.26E+06	1.37E+05	9.74E+05	6.87E+05	1.15E+06
TEP	kg	9.87E+03	7.36E+03	7.16E+01	4.42E+03	3.17E+03	1.97E+03
ULOPP	m^{2}yr	1.38E+05	1.41E+05	9.29E+03	7.73E+05	3.56E+05	3.88E+05
WDP	m^3	3.95E+04	3.95E+04	3.06E+03	1.70E+05	2.94E+05	2.12E+05

Table 6.3.3 shows that the ratio between the different fuels' impact potentials do not differ significantly to the results earlier presented for the RoPax ferry. The magnitude is however much greater, as the container ship consumes a much higher amount of fuel during a year of operation.

Table 6.3.4: Total environmental impact potential/MJ, container ship

CF	Unit	HFO	MDO/MGO	LNG	Methanol	DME	FT-diesel
ALOP	m^{2}yr	4.50E-05	4.46E-05	6.64E-06	1.43E+00	7.76E-04	8.04E-04
GWP	kg	9.32E-02	9.46E-02	9.34E-02	3.91E-02	1.76E-02	1.89E-02
PMFP	kg	1.20E-03	7.21E-04	6.33E-05	3.77E-04	2.62E-04	4.29E-04

By comparing Table 6.3.4 with Table 6.3.2 it can be seen that the environmental impact potentials are either identical or worse per MJ fuel.

Especially for PMFP is the container ship generating a higher impact compared to the ferry for the respective fuels. For the contain ship is the PMFP/MJ HFO 122% higher compared to the impact potential ratio for the ferry. The greatest difference in impact potential per MJ can be found for MDO/MGO. This is related to the low sulfur-content fuel applied for the ferry operating in a ECA. For the alternative fuels are the difference in ration varying between 22% for LNG and 82% for FT-diesel.

In terms of GWP FT-diesel shows a significant lower carbon efficiency of 48% when applied to the ferry compared to the container ship. The no significant change in GWP per MJ is found for the alternative fuels.

6.3.2 AGRICULTURAL LAND OCCUPATION POTENTIAL

As presented in Table 6.3.1 and 6.3.3 exceeds the ALOP generated by the vessels using methanol the ALOP resulting from the use of the other fuels significantly. The ALOP generated by the use of methanol is 31,826 times higher compared to HFO, and 1,748 times higher compared to FT-diesel. Because of the large difference in ALOP generated by the use of the different fuels, no bar chart is presented for illustration. However, the results from Table 6.3.1 and 6.3.3 are represented in Table 6.3.5.

Table 6.3.5: Total ALOP per functional unit, ferry and container

Fuel	RoPax ferry	Container ship	Unit
HFO	7782	48,014	m^2yr/yr
MDO/MGO	7,719	47,623	m^2yr/yr
LNG	812	7215	m^2yr/yr
Methanol	247,546,736	1,527,720,550	m^2yr/yr
DME	130,445	829,069	m^2yr/yr
FT	141,594	873,838	m^2yr/yr

The ALOP is entirely related to the WTT-phase, with the exception of bilge oil disposal, which will place a small demand on land occupation further downstream by the background processes. This small share makes up 0.055% of the ALOP related to the use of the conventional fuels for both vessels.

Table 6.3.6 presents the results from the Contribution Analysis for ALOP per process. Where nothing else is specified, the distribution applies for both vessel. The table includes processes from the background and foreground system that are contributing to more than 5% of the total ALOP.

Table 6.3.6: ALOP, contribution per process, RoPax ferry and container ship

Fuel	Process	Relative [%]
HFO	Hardwood, standing, under bark, in forest/ RER/ m^3	64.5
	Softwood, standing, under bark, in forest/ RER/ m^3	31.6
MDO/MGO	Hardwood, standing, under bark, in forest/ RER/ m^3	64.2
	Softwood, standing, under bark, in forest/ RER/ m^3	31.8
LNG, RoPax ferry	Hardwood, standing, under bark, in forest/ RER/ m^3	62.8
	Softwood, standing, under bark, in forest/ RER/ m^3	28.2
LNG, cont. ship	Hardwood, standing, under bark, in forest/ RER/ m^3	66.1
	Softwood, standing, under bark, in forest/ RER/ m^3	25.3
Methanol	Softwood, Scandinavian, standing, under bark, in forest/ NORDEL/ m^3	83.7
	Hardwood, Scandinavian, standing, under bark, in forest/ NORDEL/ m^3	13.8
DME	Hardwood, standing, under bark, in forest/ RER/ m^3	91.5
	Softwood, standing, under bark, in forest/ RER/ m^3	5.6
FT-diesel	Hardwood, standing, under bark, in forest/ RER/ m^3	92.6
	Softwood, standing, under bark, in forest/ RER/ m^3	4.5

In Table 6.3.6 it can be observed that 91.0-97.5% of the ALOP is generated by hardwood or softwood[1] under bark from forest. While the ALOP generated by methanol running vessels are caused by consumption of Scandinavian wood (NORDEL), the other fuels impose a demand on European wood (RER), which results in ALOP. With the exception of methanol, the consumption of hardwood is the main contributor of ALOP.

Because of the dominance of the WTT-phase across fuel alternatives, the relative contribution among stressors will be close to identical for both the ferry and container ship. There are however some minor differences related to the

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[1] Despite of its name, hard wood is not necessarily harder in density than soft wood. Soft wood is the main source of the world's production of timber, and includes species as Cedar, Linden, Pine and Spruce. Ash, Elm, Maple, Oak and Teak are examples of hard wood.

transportation of the fuel, as the process impose a demand on port facilities which are included in the background processes. These differences in stressor distribution are however found to be negligible, the contribution of stressors for the ferry is used as illustration for both vessels, which is presented by Figure 6.3.1. All stressors are expressing consumption/occupation of different types of land areas. Here the stressors are not expressing an emission of a substance, but consumption of a scarce resource.

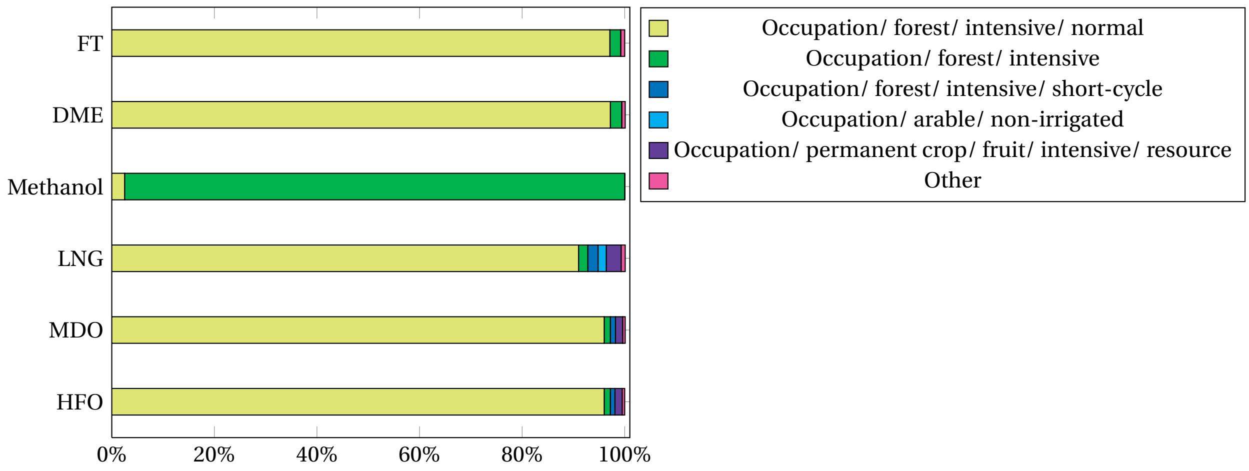

Figure 6.3.1: ALOP, contribution per stressor, RoPax ferry and container ship

It can be clearly seen from Figure 6.3.1 that the occupation of forest is the determining stressor. With the exception of methanol is *Occupation/ forest/ intensive/ normal* the main contributor of the different stressors related to ALOP. For methanol is the ALOP close to exclusively related to the stressor *Occupation/ forest/ intensive*. In terms of characterization factors, both stressors have the same contribution to ALOP per m^2yr.

The reason why the use of methanol is generating a much higher ALOP compared to the other fuel alternatives will be further assessed in the next chapter.

6.3.3 GLOBAL WARMING POTENTIAL

The total GWP associated with the production and consumption of the respective fuels associated with year of operation is presented in Figure 6.3.2 and Figure 6.3.3. The GWP generated along the production chain up to the operational-phase (WTT) is given in blue, and the impact related to the operational-phase of the vessel (TTP) is given in red. The complete data behind the figures are presented in Table 10.2.3 and 10.2.4 in Appendix **??**.

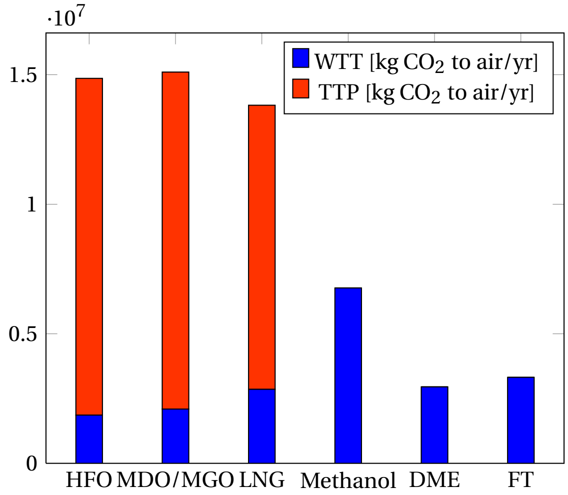

Figure 6.3.2: Total GWP per functional unit, RoPax ferry

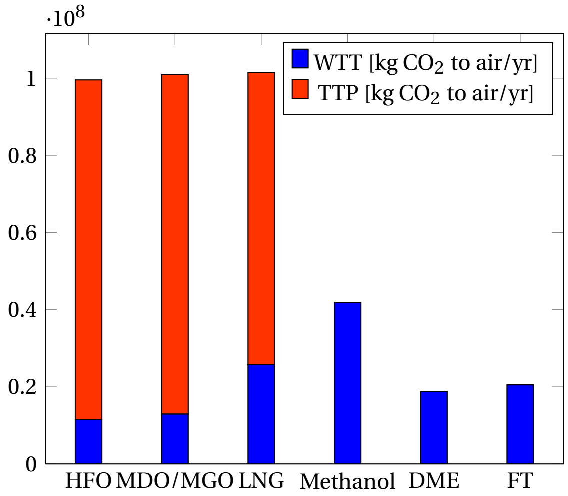

Figure 6.3.3: Total GWP per functional unit, container ship

Figure 6.3.2 and Figure 6.3.3 confirm the relative importance of the operational-phase for fossil fuels in terms of GWP. The TTP-phase makes up 86-88% of the GWP for the use conventional fuels, and 75-79% for GWP generated by LNG running vessels.

The figures also illustrate the absence of impact from combustion of biofuels. The convention of neutral biogenic CO_2 emissions was discussed in Scientific Background, Section 2.6.3. As seen for both types of vessels, the assumption made of carbon neutrality makes the biofuels most favorable compared to conventional fuels in terms of GWP.

For the ferry, a switch from HFO to biofuels would lead to a reduction of GWP equal to 54.4%, 80.1% and 77.7%, respectively. For the container ship the reduction potentials for using biofuels are 58.0%, 81.2% and 79.4%.

By applying MDO/MGO for the vessel and container, an increase of respectively 1.6% and 1.4% in GWP is experienced.

It can be observed from Figure 6.3.3 that by applying LNG to the container ship increases the GWP of 1.9% compared to use of HFO. The analysis further shows that the relative share of the WTT-phase for the LNG running container exceeds the WTT-phase for the ferry using LNG. Introducing LNG as a fuel for the ferry will not lead to significant reduction of GWP, only a small decrease of 7%.

Table 6.3.7 presents the results from the Contribution Analysis for GWP per process for the ferry. The table includes processes from the background and foreground system that are contributing to more than 5% of the total generated GWP.

Table 6.3.7 confirms the findings from Figure 6.3.2. The operational-phases makes up the main share of GWP generated by the use of fossil fuels. As the ferry is consuming about 92% of its energy during transit, it is expected that the transit on high engine load contributes to the main part of GWP generated over the year.

There are, however, more GWP allocated to the fuel production compared to the maneuvering-phase for the ferry using LNG. 7.9% of the total GWP can be tracked back to the production-phase, while the maneuvering in port makes up 5.8% of the total GWP.

Table 6.3.7: GWP, contribution per process, RoPax ferry

Fuel	Process	Relative [%]
HFO	Transit, 80% engine load	81.2
	Maneuvering/hotelling, 30% engine load	6.2
MDO/MGO	Transit, 80% engine load	80.0
	Maneuvering/hotelling, 30% engine load	6.1
	Refinery gas, burned in furnace/ RER/ MJ	3.4
LNG	Transit, 80% engine load	73.5
	Production of LNG	7.9
	Maneuvering/hotelling, 30% engine load	5.8
	Natural gas, burned in gas motor, for storage/ NO/ MJ	5.2
	Transportation of fuel	5.2
Methanol	Biomass Storage, F/PR	34.5
	Operation, lorry 3.5-20t, fleet average/ CH/ tkm	20.9
	Biomass F, at forest road	11.3
DME	Off-gas, per kg CO_2 emission	25.4
	Nitric acid, 50% in H_2O, at plant/ RER/ kg	13.7
	Operation, lorry >32t, EURO5/ RER/ tkm	7.6
	Ammonia, steam reforming, liquid, at plant/ RER/ kg	5.8
FT-diesel	Off-gas, per kg CO_2 emission	21.6
	Nitric acid, 50% in H_2O, at plant/ RER/ kg	15.8
	Electricity, biomass at power station	10.3
	Operation, lorry >32t, EURO5/ RER/ tkm	8.8
	Ammonia, steam reforming, liquid, at plant/ RER/ kg	6.6

As the GWP from the combustion of biofuels is excluded, it is interesting to see which processes contribute to the impact in the WTT-phase. For methanol it is the storage of wood chips at the bio-refinery that is responsible for the main share of GWP. This is worth noting, as emissions from biomass storage rarely are included in LCA studies.

The use of lorries for transporting forest wood and logging residues is the second largest contributor with a share of 20.9% of GWP. 32.2% of the GWP from the methanol operating ferry can be tracked back to the forestry activities associated with the forest wood feedstock.

The distribution among processes is very similar for the use of DME and FT-diesel. Off-gas from the production facility counts for 25.4% and 21.6%, respectively. The off-gas is included in the syngas conditioning and BTL-synthesis at the FT-diesel facility, and in the cleaning of syngas in the DME production chain. Consumption of nitric acid is the second largest process contributor for ferries using DME and FT-diesel. By looking at the Structural Path Analysis, see Table 10.2.7 and 10.2.8 in Appendix 10.2, the nitric acid production can be tracked back to the biomass production, modeled in the background system.

The Contribution Analysis per stressor for the ferry is presented in Figure 6.3.4.

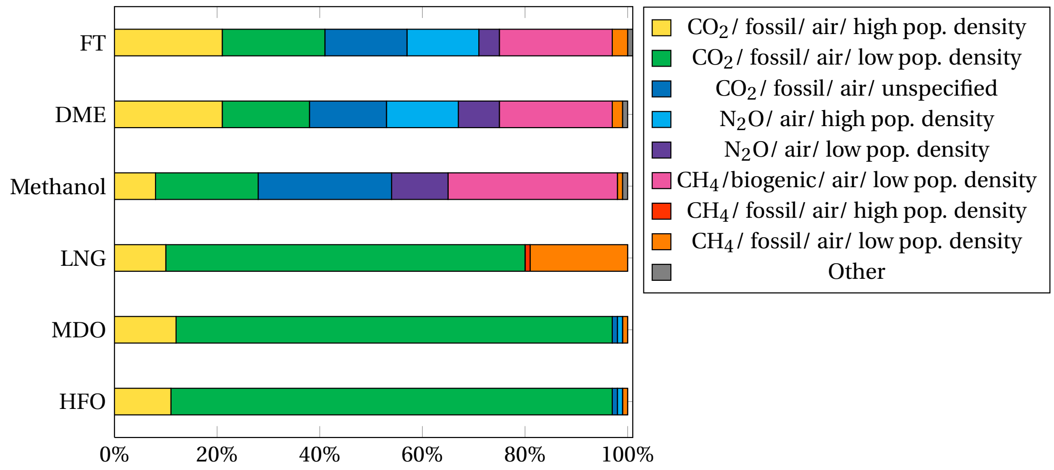

Figure 6.3.4: GWP, contribution per stressor, RoPax ferry

As the direct GHG emission factors applied have been the same for the ferry and container ship for each respective fuel, the difference in distribution of impact potential over stressors are equal to zero or negligible for the two vessels across the fuel alternatives. Small differences could be caused by rounding methods in the calculations. The transportation process of LNG is the only process modeled in the foreground that differs for the two vessels. The relative share of contribution per stressor is however not found to change notably.

Figure 6.3.4 illustrates how CO_2 emissions dominate the GWP generated from the use of fossil fuels. 97.7% of the GWP from using conventional fuels relates to CO_2 emissions, while it counts for 69.7% of GWP of the LNG running ferry. As previously mentioned, the high share of pollutants emitted in low density areas are related to the low portion of fuel consumed in the maneuvering-phase.

For LNG, 20.3% of the GWP is related to methane-emission. Methane-emissions along the LNG life cycle are related to emissions during the production, BOG-ventilation by the LNG tanker and leakages during ship operation.

As seen in Figure 6.3.4, stressors such as N_2O and CH_4 have a high relative share of GWP for the biofuels. This illustrates the importance of including various GHG emissions along the life cycle of the system and not only focus on the CO_2. The high characterization factors of N_2O and CH_4 increases its qualitative contribution to global warming. For example, N_2O has a 298 times higher impact potential compared to CO_2 over a 100 years perspective, Goedkoop et al. (2009).

Table 6.3.8 presents the results from the Contribution Analysis for GWP per process for the container ship. The table includes processes from the background and foreground system that are contributing to more than 5% of the total GWP of the container ship.

When comparing Table 6.3.7 and 6.3.8 insignificant differences are observed for the conventional fuels. The operation on high engine loads still counts for more than 80% of the total GWP. The maneuvering in ports counts for 6.9% and 6.8%, which is a very small increase compared to the share calculated for the ferry.

For the container ship using LNG, the share of GWP resulting from fuel distribution is notably increased compared to the ferry. From making up 5.2% of the total GWP the transportation of LNG to the container ship counts for 11.6%. The doubling in share can be explained by the large increase in transportation route. From Table 5.2.2 it can be calculated that the transporting distance has increased by 181% from the ferry to the container ship.

The Contribution Analysis per stressor for the container ship is presented in Figure 6.3.5. As previously mentioned, the distribution of impact is close to identical to the stressor distribution presented for the ferry in Figure 6.3.4. No additional comments will therefore be made to the distribution of stressors related to the container ship.

Table 6.3.8: GWP, contribution per process, container ship

Fuel	Process	Relative [%]
HFO	Transit, 70% engine load	47.4
	Ballast transit, 60% engine load	34.2
	Maneuvering/hotelling, 30% engine load	6.9
MDO/MGO	Transit, 70% engine load	46.7
	Ballast transit, 60% engine load	33.7
	Maneuvering/hotelling, 30% engine load	6.8
LNG	Transitnormal, 70% engine load	39.7
	Ballast transit, 60% engine load	29.1
	Transportation of fuel	11.6
	Production of LNG	6.9
Methanol	See Table 6.3.7	
DME	See Table 6.3.7	
FT-diesel	See Table 6.3.7	

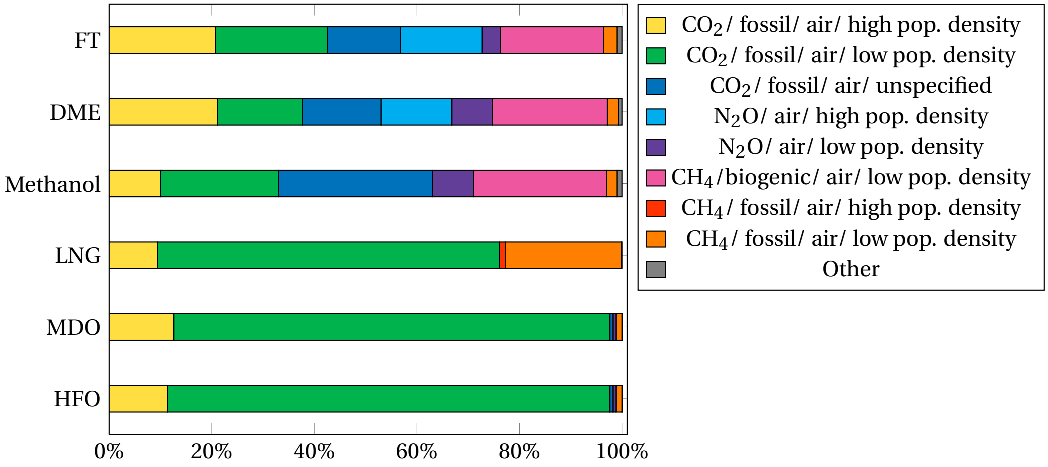

Figure 6.3.5: GWP, contribution per stressor, container ship

6.3.4 PARTICULATE MATTER FORMATION POTENTIAL

Figure 6.3.6 and 6.3.7 present the generated PMFP by one year of operation of each vessel, respective to the fuel alternatives. The PMFP generated over the WTT-phase is illustrated in blue, and the PMFP generated in the TTP-phase is marked with red. The complete data behind the figures are presented in Table 10.2.5 and **??** in Appendix ResultsAp.

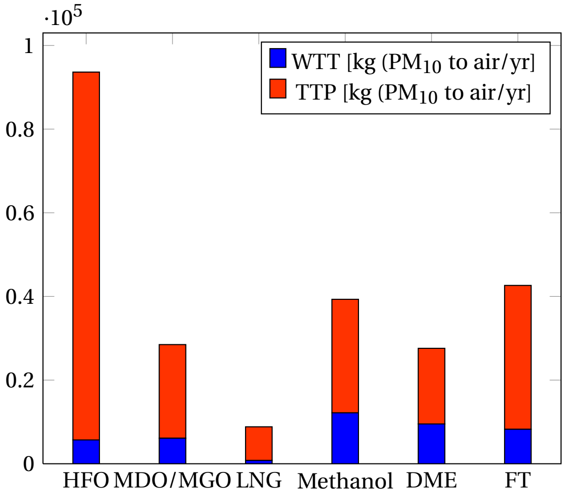

Figure 6.3.6: Total PMFP per functional unit, RoPax ferry

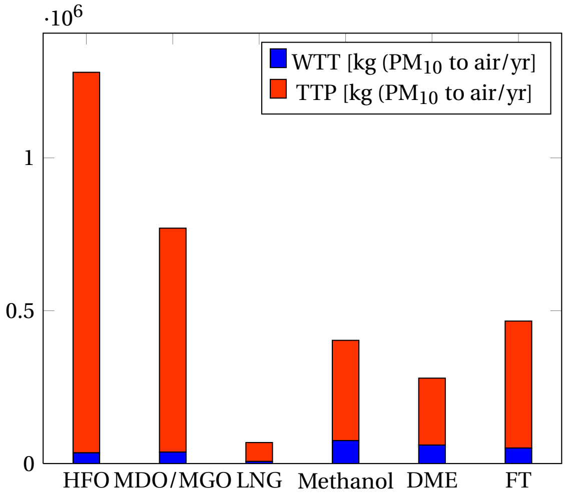

Figure 6.3.7: Total PMFP per functional unit, container ship

Figure 6.3.6 and 6.3.7 show how the TTP-phase is responsible for a significant proportion of the PMFP generated along the life cycle of all fuel alternatives. The TTP-phase is more decisive for the container ship, than for the ferry.

The two figures illustrate how specific emission factors for different loads and engine type may affect the relative impact for the fuel alternatives. The PMFP generated through combustion of biofuels appears more extensive relative to HFO for the ferry ship compared to the container ship. This is due to the fact that the ferry operates within an ECA, which requires lower emissions of SO_X, and hence less PM formation. The reference fuel that the biofuels are measured against has in other words a lower impact in the first place.

By comparing Figure 6.3.6 and 6.3.7 it is clear that the relative impact from MDO/MGO is significantly higher for the container ship. This can both be related to the PM emission factors applied, and the low sulphur content of MDO/MGO applied for the ferry.

It is found interesting that the PMFP is significant lower for the vessels using LNG. The particulate matter forming compounds reported for the production of LNG are NO_X and SO_2 as noted in the LCI. The PMFP for the WTT-phase is 86% and 80% lower compared to the HFO. In the operational-phase, SO_X emissions were neglected, while the PM emission factor was set by a default number, see Section 5.2.3.

Table 6.3.9 presents the results from the Contribution Analysis for PMFP per process for the ferry. The table includes processes from the background and foreground system that are contributing to more than 5% of the total PMFP.

Table 6.3.9 confirms that the operation of the ferry is the key contributor to PMFP. 93.9% of the PMFP generated by the HFO running ferry is generated in the operational-phase. It can be noted however, that around 10% of the impact is generated during maneuvering, which is taking place in high-density population areas. Even though only 7.3% of the energy is consumed in the maneuvering-phase for HFO and MDO, 10.7% and 11.1% of the PMFP is resulting from maneuvering. This can be linked to the increased emission factors for low-density loads, see Table 5.5.2.

For the biofuels operation of the ferry counts for 69.1%, 65.5% and 80.7%, respectively. For the ferry using methanol,

Table 6.3.9: PMFP, contribution per process, RoPax ferry

Fuel	Process	Relative [%]
HFO	Transit, 80% engine load	83.2
	Maneuvering/hotelling, 30% engine load	10.7
MDO/MGO	Transit, 80% engine load	67.5
	Maneuvering/hotelling, 30% engine load	11.1
	Natural gas, sour, burned in production flare/ GLO/ MJ	7.0
LNG	Transit, 80% engine load	82.1
	Maneuvering/hotelling, 30% engine load	8.9
Methanol	Transit, 80% engine load	63.5
	Operation, lorry 3.5-20t, fleet average/ CH/ tkm	10.2
	Maneuvering/hotelling, 30% engine load	5.6
DME	Transit, 80% engine load	60.0
	Off-gas, per kg CO_2 emission	11.3
	Maneuvering/hotelling, 30% engine load	5.5
FT-diesel	Transit, 80% engine load	74.3
	Off-gas, per kg CO_2 emission	7.0
	Maneuvering/hotelling, 30% engine load	6.4

10.2% of the PMFP can be tracked back to transportation of biomass, making it the second most important process. The impact generated from the lorries are 82% higher than the PMFP resulting from the ferry maneuvering.

Regarding the use of DME and FT-diesel, the production process *off-gas* exceeds the maneuvering-phase in terms of PMFP. As mentioned in the previous section, the off-gas is included in the syngas conditioning and BTL-synthesis at the FT-diesel facility, and in the cleaning of syngas in the DME production chain.

How the different stressors contribute to the PMFP for each fuel alternative for the ferry is presented in Figure 6.3.8.

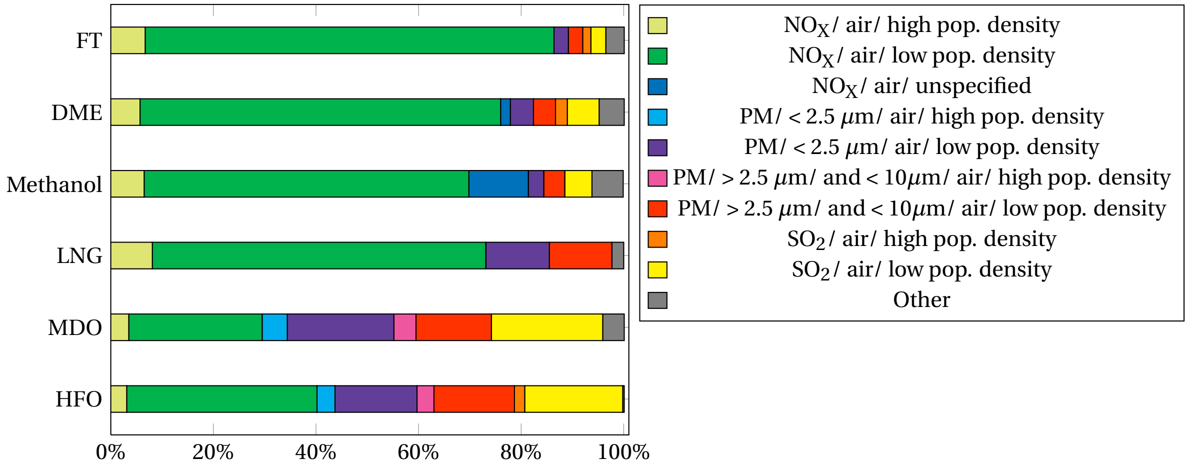

Figure 6.3.8: PMFP, contribution per stressor, RoPax ferry

Figure 6.3.8 shows that NO_X emissions are the main contributor of PMFP for the alternative fuels. NO_X contributes approximately 75-85% of the PMFP from biofuels and 73% of the PMFP generated by LNG.

Particulate matter is another important stressor when considering the conventional fuels. As the direct emissions of SO_X is set to zero for LNG and biofuels, it is clear that this stressor plays a minor role in the overall picture for the alternative fuels when considering the contribution of the TTP-phase illustrated in Figure 6.3.6 and 6.3.7.

Table 6.3.10 presents the results from the Contribution Analysis for PMFP per process for the ferry. The table includes processes from the background and foreground system that are contributing to more than 5% of the total PMFP.

Table 6.3.10: PMFP, contribution per process, container ship

Fuel	Process	Relative [%]
HFO	Transit, 70% engine load	51.5
	Ballast transit, 60% engine load	37.3
	Maneuvering/hotelling, 30% engine load	8.4
MDO/MGO	Transit, 70% engine load	49.9
	Ballast transit, 60% engine load	36.3
	Maneuvering/hotelling, 30% engine load	8.9
LNG	Transit, 70% engine load	46.1
	Ballast transit, 60% engine load	34.6
	Maneuvering/hotelling, 30% engine load	9.1
Methanol	Transit, 70% engine load	43.2
	Ballast transit, 60% engine load	31.6
	Maneuvering/hotelling, 30% engine load	6.6
	Operation, lorry 3.5-20t, fleet average/ CH/ tkm	6.1
DME	Transit, 70% engine load	41.6
	Ballast transit, 60% engine load	30.4
	Off-gas, per kg CO_2 emission	7.1
	Maneuvering/hotelling, 30% engine load	6.6
FT-diesel	Transit, 70% engine load	44.8
	Ballast transit, 60% engine load	32.7
	Maneuvering/hotelling, 30% engine load	6.8
	Off-gas, per kg CO_2 emission	5.7

By comparing Table 6.3.10 with 6.3.9, it can be seen that the operational processes have increased its relative impact across fuel alternatives. Both operation on high engine loads and low engine loads have increased on the expense of WTT-processes' share. As previously mentioned, the HFO applied for the container ship has both higher NO_X and SO_X emissions due to lower restrictions. As the NO_X emission factors applied to the biofuels depend on the reference fuel's emission factors, the impact relative to fuel consumption increases, with the exception of LNG where default values are applied. As a result, the TTP-phase becomes even more responsible for the total PMFP.

Figure 6.3.9 presents how the different stressors contribute to the PMFP for each fuel alternative for the container ship.

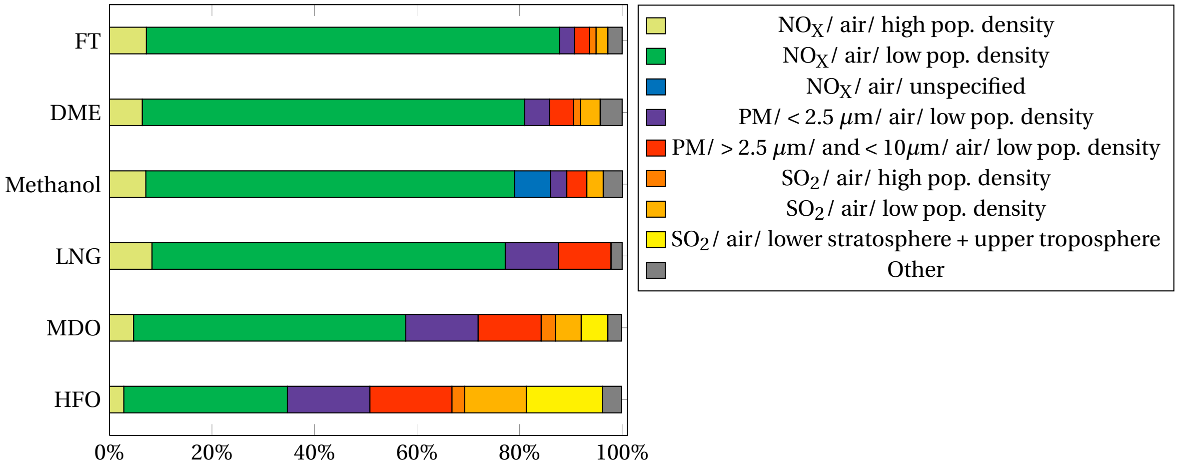

Figure 6.3.9: PMFP, contribution per stressor, container ship

It can be observed from Figure 6.3.9 that PM emitted in high density areas have a negligible share of the total PMFP generated by the container ships for all fuel alternatives. This is due to the low share of emissions occurring in maneuvering-phase compared to the pollutants emitted in the transit-phase. This can be explained by the long transit routes for the container ship, compared to the ferry, which spends a much higher proportion of its annual operation in port. It does not mean however that the PM emitted from the container ship during maneuvering is without impact to humans and the environment, as the figure only illustrates the relative importance of each stressor.

By comparing Figure 6.3.9 with Figure 6.3.8 it can be seen that NO$_X$ emissions have reduced its relative share of impact from 40% to 35%. As the ferry has a higher rpm, stricter requirements for direct NO$_X$ emissions are imposed to the ferry than for the container ship. However, the container ship does not experience a larger share of contribution from NO$_X$ emissions, as the vessel also has higher SO$_X$ and PM emission factors.

7

LIFE CYCLE INTERPRETATION

7.1 INTRODUCTION

In this chapter a Sensitivity Analysis will be performed to assess the results' dependency on the choices made regarding methods and data in the LCI The Sensitivity Analysis will focus on the main contributing factors from the previous chapter.

The results from the LCIA and Sensitivity Analysis will then be further discussed and interpreted in Section 7.3. Results referred to in the text can be found in Appendix 10.3, while the complete data sets from this chapter can be found in Appendix D.

7.2 SENSITIVITY ANALYSIS

7.2.1 ENGINE EFFICIENCY AND EMISSION FACTORS

It was found in the results that the ship operation was the main contributor of GWP for the fossil fuels, and the crucial life cycle-phase for PMFP for all fuel alternatives. As the impact from the TTP-phase is a direct consequence of the fuel combustion, it is evident that engine efficiency is a decisive factor for the overall environmental performance of the fuel alternatives.

Large marine engines are commercial off-the-shelf products; each with their own characteristics. In the inventory analysis, it was assumed that the slow speed engine would have a 10% higher efficiency compared to the efficiency measured for the medium speed engine.

The way the system is modeled, as described in the Methodology chapter, Section 4.5, the fuel consumption is completely disproportional to the engine efficiency. As the engine efficiency is improved by a given percent, impact potentials will be reduced by the same share. It the engine efficiencies have been overestimated, the impact will increase correspondingly. It is shown that the engine efficiency decreases with lower engine loads. Improved engine efficiencies at low loads would offset some of the environmental impact imposed to the harbor areas.

As a container ship and a RoPax ferry varies both in carrying capacity and utility, their engine performances are expected to vary in terms of emission factors as well. This was confirmed by emission inventory guidebooks, Trozzi et al. (2009).

As noted in the Literature Review, Section 3.5, the engine technology is decisive for some pollutants, e.g. CO, VOC, NO_X and PM which are derived from soot. It is therefore necessary to test the robustness of the results, in order to asses how sensitive the overall impact potentials are to these substances.

As the literature on the topic is limited for marine engines, high uncertainty is related to the emission factors of biofuels. The emission factors applied are therefore in large extent based on assumptions. As SO_X emissions are eliminated from combustion of biofuels, the NO_X and PM emission factors have been adjusted in order to check the sensitivity of the derived PMFP.

The Contribution Analysis for the alternative fuels showed that NO_X emissions are responsible for around 75-85% of the generated PMFP. As the operational-phase is contributing to 65.5-91.0% of the total PMFP for these fuels, it is believed that the results will be sensitive to the NO_X emission factors applied for the combustion process.

Figure 7.2.1 and 7.2.2 illustrate the change in PMFP per functional unit by adjusting the NO_X-emission factor for biofuels by 10% from the originally applied values, where the resulting increase in impact is marked in purple. The numbers behind the figures are presented in Table 10.3.2 in Appendix 10.3.

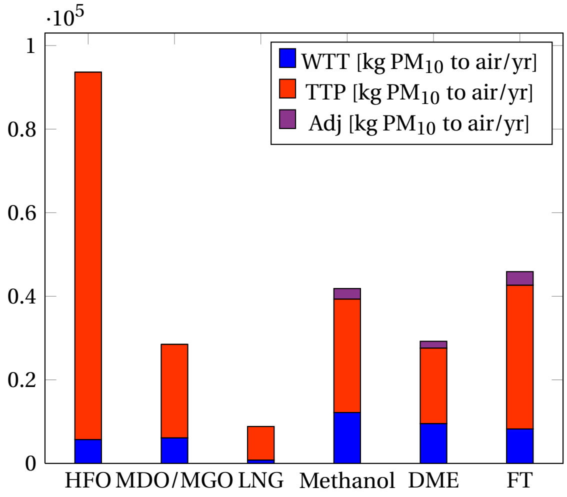

Figure 7.2.1: PMFP per functional unit, RoPax ferry, NO_X-adjusted

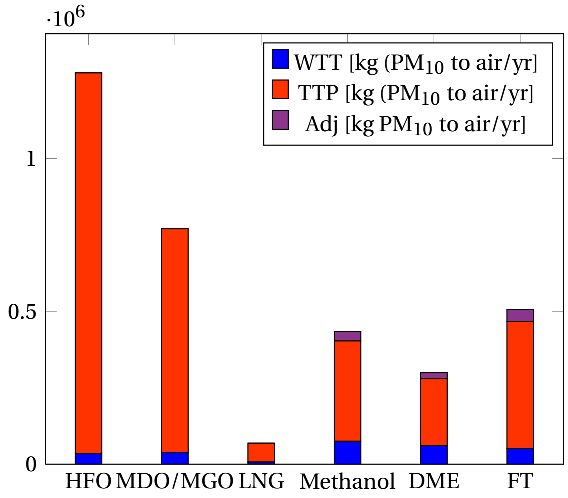

Figure 7.2.2: PMFP per functional unit, container ship, NO_X-adjusted

Figure 7.2.1 and 7.2.2 illustrate a strong correlation between the total PMFP and the NO_X emission factors. The results show an increase from 5.6% for the DME running ferry, to an increase of 8.4% for the container ship running on FT-diesel. The figures illustrate that major changes in NO_X emission factors would be necessary to offset the PMFP reduction obtained by applying biofuels in stead of HFO for both vessels.

In order to test how a drastic change in assumptions would affect the overall results, the PM emission factors for biofuels were reduced by 50% compared to HFO, instead of 95% which was applied in the LCI. The adjustment was also made for the combustion of LNG for both vessels. The PM-emission factor originally applied for LNG was taken from literature, but the low PMFP values suggest that the emission factor might have been underestimated.

As comparison to the magnitude of these adjustments, the PM emission factors initially applied for MDO/MGO are 61% lower compared to HFO for both vessels.

The resulting PMFP per functional unit is presented by Figure 7.2.3 and 7.2.4, where the resulting increase of impact is marked in purple.

Figure 7.2.3 and Ferry 7.2.4 show respectively that the PMFP for LNG increased by 63.5 and 75.5%. To apply a 50% reduction of the PM emission factors for LNG compared to HFO is a drastic leveling of the emission factors originally applied. For example will the emission factor for ferry maneuvering increases 24 times, from 0.05g/kWh to 1.21g/kWh. Figure 7.2.3 and 7.2.4 show that the container ship is more sensitive to change in PMFP compared to the ferry. Despite of the fact that the total PMFP for LNG increased 74% for the ferry and 227% for the container ship, the results confirm that LNG has significant environmental benefits considering PMFP, compared to HFO.

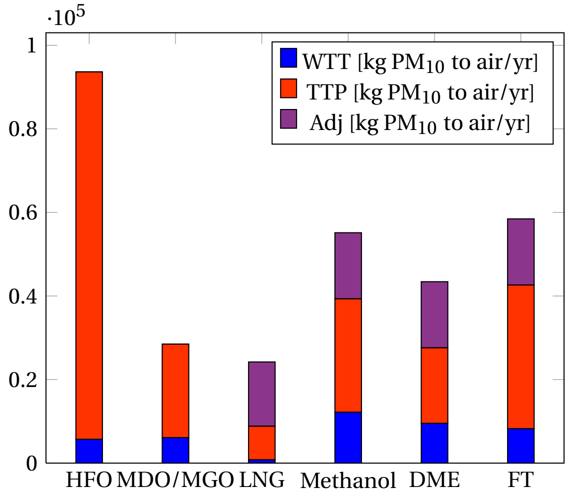

Figure 7.2.3: PMFP per functional unit, RoPax ferry, PM-adjusted

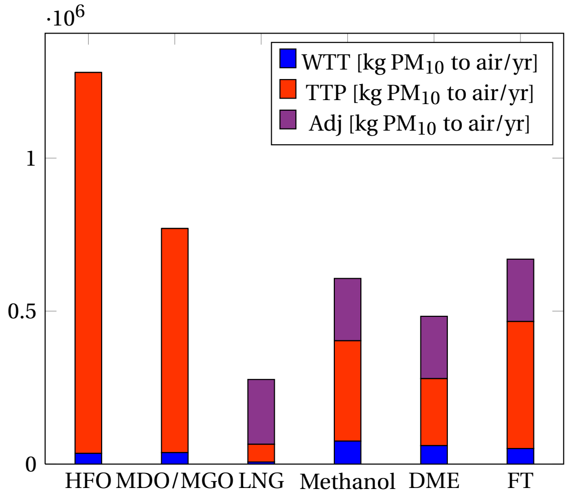

Figure 7.2.4: PMFP per functional unit, container ship, PM-adjusted

Direct emissions of PM from the production of LNG was not reported by Statoil, and therefore not included in the LCI. It is possible that an inclusion of these emissions would increase the impact potential. However, by looking at the relative share of the WTT-phase for conventional fuels, it is unlikely that such an inclusion would lead to a significant change of the PMFP with respect to the reference fuel.

The adjustment in PM-emission factors for biofuels resulted in an increase of PMFP for the ferry equal to 28.7%, 36.5% and 27.1%, respectively. The measured increase for the container ship equaled to 33.6%, 42.2% and 30.4%. This shows that the PMFP from DME is most sensitive to adjustments of direct PM emissions, while the FT-diesel life cycle is the least sensitive to the adjustment when comparing the biofuels.

Despite of the almost doubling of PM emissions during combustion, the use of biofuels results in significant reductions compared to HFO. However, Figure 7.2.3 presents MDO/MGO and LNG as superior fuel alternatives regarding PMFP for the ferry. For the container ship, all the alternative fuels are resulting in lower PMFP compared to the conventional fuels.

The results from the contribution analysis showed a relative small share of PM-associated PMFP compared to NO_X emissions for the alternative fuels. It is therefore interesting to see that change in PM-emission factors still create a notable difference to the overall impact potential in Figure 7.2.3 and 7.2.4.

7.2.2 ALOP FROM METHANOL

In the previous chapter, the results revealed methanol production from wood as a significant generator of ALOP, beyond comparison to the other fuel alternatives. In contrast to the short-rotation wood applied for DME and FT-diesel production, Scandinavian wood was used as feedstock in the production of methanol. Table 7.2.1 presents the stressor factors linked to one cubic meter of *softwood, under bark from forest.* The table shows how the background system in Ecoinvent 2.2 database evaluates the amount of stressors related to each product.

As seen in Table 7.2.1, the rate of land occupation for Scandinavian softwood is evaluated to be 4.26 times higher than the European softwood. Unfortunately, the LCA report on Scandinavian wood used by Ecoinvent database is not available for the author at the moment. The background for the greater impact associated with Scandinavian wood consumption compared to European wood therefore remains unknown. One important factor is expected to be the rotation time. Because of the colder climate it is expected that trees regrow slower in Scandinavia than in the average European forest.

Table 7.2.1: Stressor factors per type of softwood, standing under bark, in forest

Stressor factors	unit	RER	Scandinavian
Occupation, forest, intensive, normal/ resource/ land	m^2yr	977	4160
Transformation, from forest, extensive/ resource/ land	m^2	8.14	27.7
Transformation, to forest, intensive, normal/ resource/ land	m^2	8.14	27.7
Wood, soft, standing/ resource/ biotic	m^3	1.1	1.1

In order to test the differences stated in Table 7.2.1, the production route for methanol was adjusted for the ferry by substituting Scandinavian wood with European average wood. No adjustments were made in terms of volume, by assuming that the wood type share the same characteristics. The resulting ALOP from adjusted system is marked as *Methanol2*.

One methanol production process from the Ecoinvent database has also been included in the graph. *Methanol3* represents the ALOP resulting from producing the same amount of methanol using the unit process *methanol, from biomass, at regional storage/ CH* from the Ecoinvent database. The syngas production and methanol synthesis are identical to the processes modeled in the LCI for methanol in this study. However, the feedstock applied for this unit process is evaluated as relevant for biomass gasification in Switzerland (CH), and compromises European forest and waste wood, Jungbluth et al. (2007a).

The resulting impact potential per functional unit from the three methanol alternatives for the ferry is presented in Figure 7.2.5.

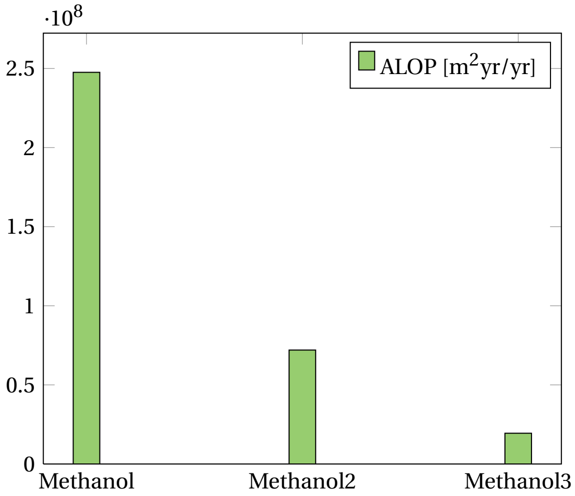

Figure 7.2.5: ALOP per functional unit, RoPax ferry, various types of methanol production routes

Figure 7.2.5 clearly illustrates how the impact can be significantly reduced by switching the Scandinavian wood feedstock to European. This also states how sensitive the biofuel's performance is to the feedstock. Even though wood from forest may be evaluated as sustainable and environmental friendly, there are clearly variations among the different types of wood.

It can be further noticed that the methanol production route modeled by Ecoinvent has an environmental benefit in terms of ALOP compared to the production route modeled for this study. This might be related to a higher share of residual wood, or that the processes upstream to the gasification are more efficient compared to the system modeled by Bright and Strømman (2009) which was adopted in this study.

7.2.3 CARBON NEUTRALITY AND TEMPORAL SCOPE

The results showed a remarkable reduction in GWP when biofuels were applied for marine vessels. A reduction of 80% was achieved by substituting HFO with DME for both vessels. However, the LCIA results do not take into account the climate impact of biogenic CO_2 emissions. As the convention of carbon neutrality is disputable, it is found necessary to assess the effect of including impact from biofuel combustion.

In order to do so, a GWP characterization factor of CO_2 equivalents per emitted biogenic CO_2 is applied based on the research by Cherubini et al. (2011). The characterization factors are estimated for biomass depending on its rotation time and the time horizon evaluated. These factors are presented in Table 7.2.2.

In order to demonstrate the importance of the time period considered a second sensitivity test is performed. The evaluated time horizon is here set to 20 years.

Table 7.2.2: Biofuels characterization factors

Stressor	Feedstock	Rotation time	Unit	GWP20	GWP100
Carbon dioxide, biogenic	Scandinavian wood	100 years	kg CO_2 eq	0.96	0.43
Carbon dioxide, biogenic	Willow-Salix	4 years	kg CO_2 eq	0.11	0.02

The direct biogenic CO_2 emissions from combustion are calculated based on the carbon content previously presented in Table 2.7.1. The equation for calculating the emission factors is presented in Appendix 10.3.

To be able to make a fair comparison, the characterization factors for the other GHG must adjusted for the new time horizon as well. As found in the previous chapter, CO_2, CH_4 and N_2O emissions are the key contributors to GWP. Adjustments to the amount of these emissions were made in the foreground inventory for each biofuel and LNG based on the characterization factors presented in Table 7.2.3. An alternative would be to directly change the characterization factors, but no such option was available for the LCA software used in this study. Since the GWP of using conventional fuels is mainly dependent on CO_2, which is the reference substance for calculating GWP characterization factors, no adjustments were made to the inventory of conventional fuels.

The resulting GWP values per functional unit are presented in Figure 7.2.6 and 7.2.7. The numbers behind the figures are presented in Table 10.3.1 in Appendix 10.3.

Table 7.2.3: Climate change characterization factors

Stressor	unit	GWP20	GWP100
Carbon dioxide, fossil	kg CO_2 eq	1	1
Dinitrgoen monoxide	kg CO_2 eq	289	298
Methane fossil/biogenic	kg CO_2 eq	72	25

Figure 7.2.6 shows that when assuming a rotation time of 4 years and assessing the GWP over a 100 years time period, significant reduction can still be achieved by substituting the fossil fuels with DME or FT-diesel. The small characterization factor added for biogenic CO_2 emissions from DME and FT-diesel life cycle did not lead to a noteworthy increase of GWP. The adjusted reductions are equal to 78.6% and 76.0%, respectively.

Switching from HFO to methanol for the ferry now results in a reduction of GWP equal to 19.6%. The figure clearly demonstrates how the convention of carbon neutrality favors biofuels with longer rotation time.

Figure 7.2.7 illustrate how the results depend on chosen time reference and the modeling method of biogenic carbon impact. The GWP is drastically increased for LNG and methanol when considering a 20 years time horizon. The associate GWP for the two fuels exceeds the impact potential of conventional fuels. The GWP for DME and FT-diesel has also notably increased, but is still low compared to the GWP for conventional fuels.

A shorter time horizon does not only affect the characterization factors applied for biogenic CO_2, it also increase the impact from CH_4 emissions by 188%. The impact from N_2O was reduced by 3%. The high GWP related to LNG and

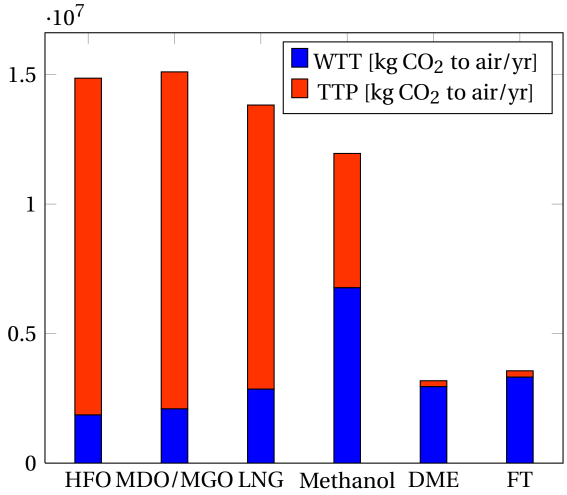

Figure 7.2.6: GWP per functional unit, RoPax ferry, time horizon 100 yr

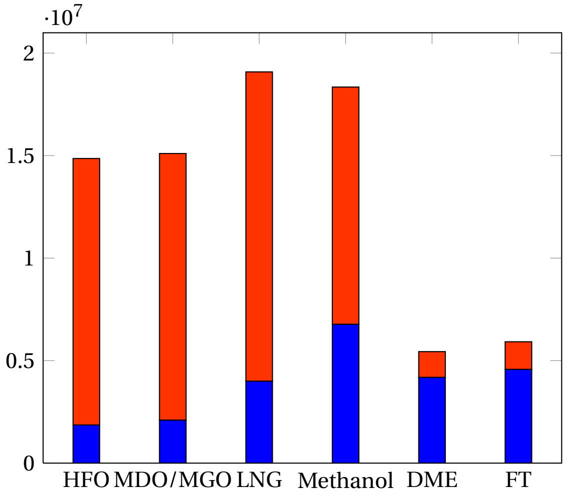

Figure 7.2.7: GWP per functional unit, RoPax ferry, time horizon 20 yr

methanol consumption can be explained by the high relative share of CH_4, which has almost tripled its contribution to GWP. The GWP of DME and FT-diesel, when applying a 20 year time horizon, is about 30% higher compared to the base case.

The GWP factors derived for a 100 years time horizon are widely accepted among climate scientists, and was applied in the Kyoto Protocol, Forster et al. (2007), Guinée (2002). This research does not intent to question this methodology, but aims at highlighting the sensitivity of the results presented in the study. What Figure 7.2.6 and 7.2.7 demonstrate is how results can significantly depend on the scope and system boundaries. The results show that LNG and biofuels from long-rotation wood are not effective as short-term mitigation measures against climate change.

7.2.4 BOIL-OFF-GAS

As mentioned in the Scientific Background, Section 2.7.2, boil-off-gas (BOG) is a natural occurring phenomenon during storage of LNG. In the LCIA of the production and distribution of LNG it was assumed that the BOG generated during the transportation of the fuel was directly ventilated to air.

The modeled BOG compromises of methane, ethane and propane, which are characterized as contributors to climate change by the ReCipe 2008. It is therefore interesting to asses how the released BOG affect the total GWP of the system.

A complete ventilation to air must be considered as the worst-case scenario. In the sensitivity analysis the emission of BOG is completely excluded by assuming that the gas is fully recovered at the ship. The BOG can be re-liquefied or be used as a fuel. This could either lead to higher energy consumption at the fuel tanker or lower fuel consumption. No changes is however made to the freight's operating inventory in order to simplify the modeling.

The results from the sensitivity analysis are presented in Table 7.2.4.

For the container ship, the result was a 69.7% reduction of the GWP from the transportation process. This contributed to a 8.3% reduction of the overall GWP. For the ferry, the GWP of fuel transportation was reduced by 72.1%. However, due to the low relative impact of this process, the overall reduction of GWP was only equal to 3.8%.

This shows that it is possible to reduce the impact from LNG distribution significantly by reducing BOG emissions, but how this will affect the overall impact of LNG life cycle depends on daily BOG-rate and transporting distance.

Table 7.2.4: Sensitivity analysis of BOG

Vessel	LNG distribution kg CO_2 eq/yr	LNG distribution adj. kg CO_2 eq/yr	rel.process %	rel.system %
RoPax ferry	726,342	202,323	-72.1	-3.8
Container ship	12,010,064	3,637,267	-69.7	8.3

7.2.5 BIOMASS STORAGE

A biomass storage have two main advantages for the fuel producer: a biomass reserve minimize the risk of supply interruption and the energy consumption related to drying of fresh biomass can be reduced.

However, the results showed that 34.5% of the generated GWP from the use of methanol was related to storage of biomass. The emissions from biomass storage was modeled as CH_4 and N_2O emissions, in accordance with the study by Bright and Strømman (2009). It was shown in the contribution analysis that 34.6% of the GWP could be related to emissions of these two substances along the life cycle.

Study by Jungbluth et al. (2007b) which makes up the inventory for DME and FT-diesel includes emissions from biomass storage. However, these are modeled as biogenic CO_2 emissions. As it has earlier been discussed, the GWP induced by biogenic CO_2 emissions is excluded from the LCIA in this study. The result is that the biomass storage in the DME/FT-diesel life cycle appears climate neutral, while the biomass storage related to methanol production is modeled with highly potent GHG, which results in a high GWP per functional unit.

To check this sensitivity, the emission factors for forest wood storage has been applied for the storage of Willow-salix, which is used as feedstock for DME and FT-diesel. This includes CH_4 and N_2O emission factors based on the carbon and nitrogen content of the biomass, which equals to 48 dry wt. %, and 0.49 dry wt. % for the Willow-Salix, Jungbluth et al. (2007b). The results are presented in Figure 7.2.8, where the resulting increase in GWP is marked in purple for DME and FT-diesel.

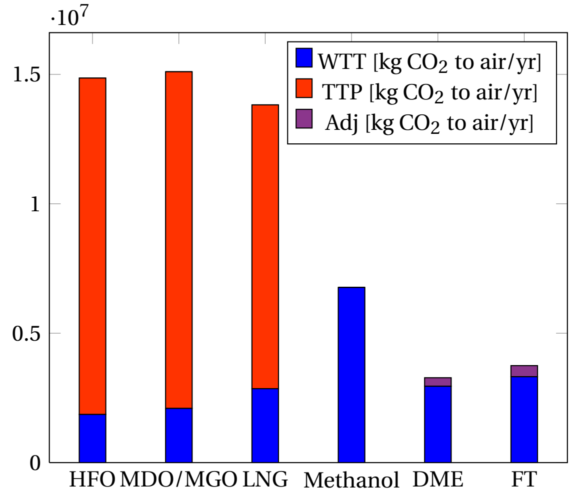

Figure 7.2.8: GWP per functional unit, RoPax ferry, adjusted biomass storage

Figure 7.2.8 shows an increase in GWP for DME and FT-diesel equal to 11.1% and 12.9%. Even though the increase looks small relative to the GWP of conventional fuels, this is actually a significant increase for the two biofuels' life cycle alone.

This is a key issue when comparing different LCA studies, system boundaries, allocation and modeling choices might vary. This study has shown that these factors can be determining in terms of the GWP of biofuels.

7.2.6 ENERGY CONSUMPTION IN BIOREFINERIES

One main weakness of the methanol production route is that the syngas production and methanol synthesis is not coordinated. The energy released during exothermic processes, i.e. methanol synthesis, can be utilized by endothermic (energy consuming) processes such as drying of biomass.

A study by Zhang et al. (2008) states that economic, environmental and social benefits can be obtained through utilization of the waste of some processes as resource for other processes. In the case of methanol production, an integration and optimization of the different conversion stages could make the system more energy efficient.

As the biorefineries were modeled as self-sufficient in terms of energy, where biomass was burned to produce the required heat and electricity, an improved energy efficiency also implies reduced resource extraction. For the methanol life cycle it was found that 32.2% of the total GWP could be related to forestry operation and feedstock transportation. By reducing the required volume of biomass per kg methanol would therefor reduce the GWP of the system. For FT-diesel 10.3 percent of the GWP per functional unit is resulting from electricity production from biomass.

Figure 7.2.9 shows how the three impact potentials for the RoPax ferry vary when the efficiency of the methanol production is improved. The production volume of syngas has been reduced to the level required by the methanol synthesis, while syngas production for electricity and heat production has been excluded. The data from the Figure is resented in Table 10.3.3 in Appendix 10.3.

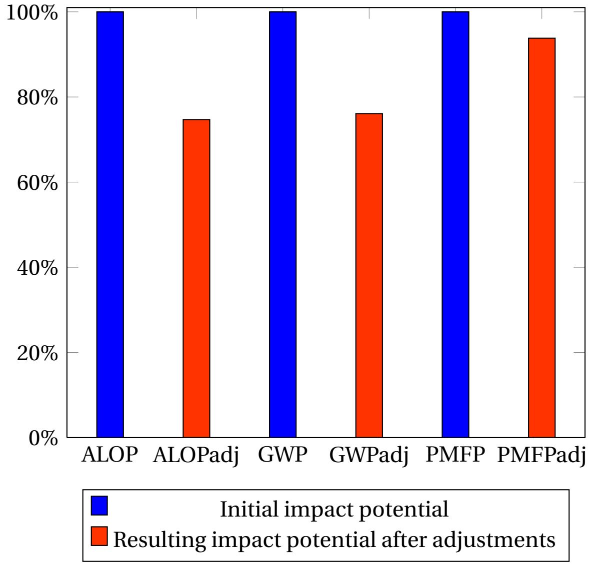

Figure 7.2.9: Relative change in impact potential, resource efficiency adjusted, RoPax ferry

The results illustrate how the environmental impact along the methanol lifecycle is sensitive to the resource and energy efficiency of the biorefinery. However, these results should be further adjusted as the electricity and heat production must be replaced it the plant operation should be maintained. Further research should be done to assess the consequence of substituting this energy carrier with electricity or fossil fuels.

7.3 DISCUSSION

7.3.1 EVALUATION OF MARINE POLICIES AND REGULATIONS

The motivation behind the earlier and current marine policies has been to reduce the environmental impact of the conventional fuels. The regulations and policies the past decades have concentrated on NO_X and SO_X emissions, which has been proven to be the main contributors to PMFP for the assessed fuels. Regulating NO_X emissions will also be of great importance if some of the alternative fuels assessed are to be implemented in a larger part of the global fleet, as the results have shown that NO_X is the key contributor of PMFP for alternative fuels. Recently, energy efficiency measures have been imposed, i.e. the EEDI and SEEMP, in order to reduce the fuel consumption and further the GWP.

What can be discussed after considering the results from the LCIA, is if the current policies are sufficient to not only facilitate implementation of alternative fuels, but also be able to regulate other environmental impacts which previously have not been of concern to the marine sector.

For conventional fuels, the assessed impact potentials have primarily been related to direct emissions from fuel combustion. The LCIA for biofuels has shown that processes upstream to the operational phase can be of great importance when considering environmental impacts from biofuels. For example, if carbon neutrality is assumed for biofuels, the generated GWP and ALOP will exclusively be a result of the WTT-phase of the fuel life cycle. The current regulations for the marine sector does not include any tools to minimize the environmental impact in the production phase.

A possible scenario is a *problem shift*, where the environmental impact imposed by shipping is moved to the fuel industry. For example, the results show a large ALOP related to biofuel production compared to conventional fuels, but it is unlikely that the IMO will enforce regulations on required level of ALOP per MJ marine fuel. It is maybe possible to implement a trading scheme for CO_2 permits, but the permits will deal with the direct CO_2 emissions, not the emissions related to the fuel production. However, it does not mean that the emissions from the fuel producing industries are not subjected to own environmental regulations.

The issue of responsibility is an ongoing debate when speaking of environmental impacts. One point of view is that the global fleet to a large extent delivers a service in form of transporting goods. The transporting sector works in this case as a process in the product's life cycle, where the demand on the shipped goods is a result of the consumption of goods. A question is then if the consumer should take a larger responsibility for the impacts generated downstream in the product's life cycle.

Environmental impact associated with direct emissions from fuel combustion can be tracked to the responsible ship owner. However, if the environmental impact occur further down stream in the fuel life cycle, the current policies are insufficient in placing the responsibility of to the marine sector. If not holistic information about the various impacts from the alternative fuels are provided, a consequence might be uncritical use of biofuels because the general understanding implies that biofuels are "environmental friendly". Such a *rebound effect* implies that the efficiency gain of introducing a technology causes an increase in consumption, which will offset some of the advantage of the efficiency gain.

The goal must be to impose regulations to the marine sectors which takes environmental impacts along the fuel's life cycle into account, so that the price of shipping reflects the associated externalities[1].

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[1] *Externalities* refers to situations when the effect of production or consumption of goods and services imposes costs or benefits on others which are not reflected in the prices charged for the goods and services being provided, OECD (2003)

7.3.2 EVALUATION OF RESULTS

For the RoPax ferry using conventional fuels, i.e HFO and MDO/MGO, the annual GWP was measured to be 0.0149 and 0.0151 million tonnes CO_2 equivalents, respectively. The results are approximately 30% lower than the average CO_2 emissions per year for RoPax ferries, earlier presented in Table 2.4.1. The emissions data presented in Table 2.4.1 are estimated emissions from ship operation in 2007, representing an average of 2,819 RoPax ferries of different size, operational pattern and engine characteristics. The derived results are therefore found credible.

For the container ship, the GWP from using conventional fuels were measured to be 0.0995 and 0.101 million tonnes CO_2 equivalents. These are results which exceed the estimated average for container ships by 183-186%. However, this average represents 4,264 container ships of various size and operational patterns. More specific numbers for ship containers of the size 3,000-5,000 TEU give an average annual CO_2 emission of 0.084 million tonnes. When comparing this amount with the obtained results from this study, the results are found most reasonable with respect to the inclusion of WTT-emissions.

Few life cycle studies have been performed on marine fuels, and key findings from these was previously presented and discusses in Chapter 3. Results from the well-to-propeller studies considering impact from GHG have been presented in Figure 7.3.2, next to the results obtained in this study in Figure 7.3.1.

It must be noted that life cycle studies cannot be directly compared, as they might vary in scope and system boundaries. For the literature presented, DME is the only fuel which has the same feedstock as the DME assessed in this study. The FT-diesel is not produced from biomass, but natural gas, and the GHG emitted during combustion is therefore included in red. The results for methanol presented from the literature is produced from black liquor. Despite of the difference in product route, it is believed that the presented GWP from past studies are relevant for comparison. Key information on the fuel cycles presented from literature is given in Table 7.3.1. The table also includes results obtained for methanol and DME produced from natural gas.

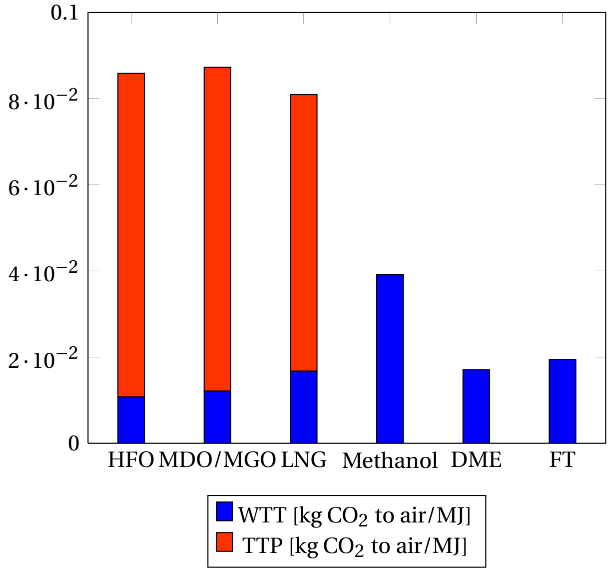

Figure 7.3.1: GWP/MJ fuel, RoPax ferry

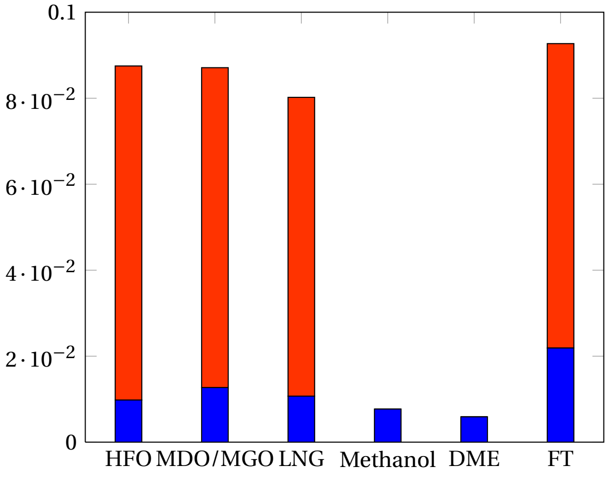

Figure 7.3.2: GWP/MJ fuel, literature

Figure 7.3.2 and Table 7.3.1 show that the derived GWP over fossil fuels' life cycle are in compliance with the results presented in the literature. The highest deviation is found for HFO, which equals 1.9%. However, significant deviation in results are found for the methanol and DME.

Methanol is the biofuel which has the highest deviation of 80.3% compared to fuel route assessed in this study. It can be repeated that 34.5% of the GWP derived for methanol in this study was related to biomass storage, which is not

Table 7.3.1: Allocation of impact, LNG production facility

Fuel	Reference	Note	kg CO_2 eq/MJ fuel	Deviation
HFO	Verbeek et al. (2011)	Crude oil transported 8,000km to Europe and processed	0.0869	1.9 %
MDO/MGO	Verbeek et al. (2011)	See HFO	0.0871	-0.2 %
LNG	Verbeek et al. (2011)	Produced on-shore in Qatar and transported to Europe	0.0792	-0.9 %
Methanol	Edwards et al. (2004)	Produced from black liquor	0.00771(TTP)	-80.3 %
Methanol	Edwards et al. (2004)	Produced from natural gas	0.02325(TTP)	-40.5 %
DME	Hansen and Mikkelsen (2001)	Produced from black liquor	0.00590(TTP)	-65.5 %
DME	Edwards et al. (2004)	Produced from natural gas	0.02025(TTP)	11.8 %
FT	Edwards et al. (2004)	Produced from natural gas	0.0219(TTP)	12.9 %

included in the study by Edwards et al. (2004). If the GHG emissions related to biomass storage is excluded from the methanol life cycle the deviation would be reduced to 54.4%. The study by Edwards et al. (2004) also assess the GHG from methanol produced from natural gas. The GHG emissions along the TTP-phase is 40.5% lower than this study's methanol production chain. The GWP of DME produced from natural gas has 11.8% higher GWP compared to the the TTP-phase in this study.

The study by Bengtsson et al. (2012) assess the GWP, AP, Eutrophication potential and emission of particles for a RoPax ferry operating in the Baltic sea. Unfortunatly, the results are only presented on a functional unit basis, making it hard to compare the results. However, the study finds a much higher amount of life cycle emissions of particles for synthetic biofuels relative to HFO, than the results obtained in this study. The study by **?** further concludes that LNG generates the lowest impact in terms of particulate matter, which was also found by this LCIA. Even though the results for each fuel vary significantly, the results obtained in the literature support the conclusion of a significant reduction potential of global warming when substituting fossil fuels with biofuels. The relative differences in GWP among the fuel alternatives are found to be matching this study's results, with the exception of some what lower GWP for LNG.

The significant disparity for synthetic fuels (i.e. methanol, DME and FT-diesel) indicates that the results are highly case specific and sensitive to the system boundaries. However, more studies should be compared in order to draw conclusions of potential over- or underestimating of the GWP for the biofuel life cycles assessed in this study.

As the background data of the production of biofuels applied in this study is based mainly on data relating to demonstration and/or pilot-scale installations, and is not modeled as an integrated process in terms of energy efficiency, it is likely that the GWP of biofuel production in this study has been overestimated.

7.3.3 LIMITATIONS OF THE STUDY

A LCA provides large amount of data describing the environmental performance of a system. Limitations and challenges of the LCA methodology applied were earlier summarized in Chapter 4. It was mentioned that the results from the LCIA addresses only the environmental issues that are specified in the goal and scope. The limitations of this case study will now be presented.

The results must be studied with precaution, as the system boundaries might lead to a limited data foundation for some of the impact categories. For example, Human Toxicity Potential is highly related to heavy metals, but as the construction of the ship is not included, these results are not suitable for making conclusions of the total impact to Human Toxicity from shipping, only the life cycle of the actual fuel. Another impact category which should be evaluated with precaution is water depletion potential. Effects of water utilization differ a lot depending on local conditions as ground water level, quality of precipitation, Jungbluth et al. (2007a). For example, water depletion would have a much larger effect to the environment in dry areas, such as southern Europe, compared to Scandinavia which has a colder and wetter climate.

History has shown that oil spills from vessels, in particular oil tankers, can have disastrous consequences for the wildlife and the environment. The Exxon Valdez oil spill in Prince William Sound, Alaska in 1989, and the Full City accident at Langesund, Norway in 2009 are examples of events where the shipping industry is directly involved. These accidents are not linked to the fuel choice of the vessel, but indicates what damage shipping can bring upon the environment.

LCA is unsuitable as a tool to assess the risk associated with different vessel operations. For example, use of conventional fuel impose a risk of oil spills, while use of LNG has a lower risk of environmental impacts related to fuel spills, as the fuel evaporates in natural conditions.

As noted in the definition of the 18 midpoint impact categories in Table 6.1.1, the scale of impact is varying between global, regional and local. For example, the location of the GHG emission source is trivial to the actual impact of the substances released to air. Pollutants causing marine eutrophication and ecotoxicity are examples of local problems.

In the case of the RoPax ferry which is operating in a limited geographical area, the results from the LCIA can be of great value to understanding the potential environmental impacts of the ship operation. For the container ship, which is operating over multiple world regions, the derived impact potentials for local impact categories will be of lower utility value, as it is hard to link the total impact to the local environments along the shipping route.

The consequences of airborne pollutants are also depending on the fate and transport of the released substances, which are a result of weather conditions and air composition. These are examples of factors that are not implemented in LCA. Other examples related to shipping are weather conditions, water streams, and marine vegetation and wildlife. Comprehensive knowledge about the marine ecosystems would be necessary to completely understand the effect of the imposed impact potential.

Unfortunately, in LCA it is not possible to distinct use of land which is already been cultivated and newly cultivated fields. The occupation and transformation of land might lead to reduction of biodiversity. A LCA neither assess the effects of air or waterborne pollutants on biodiversity.

LCA does not evaluate the economic efficiency of the system. The study does therefore not say anything about the abatement cost of introducing alternative fuels. Further, it is not assessed if it is environmental efficient to utilize biofuels in a transporting sector which is currently more energy efficient than most other transporting modes. A larger reduction in environmental impacts of various geographical scale can possibly be achieved by utilizing biofuels in more fossil-intensive processes.

Process-based LCA has the limitation of only assessing the system separated from the global economy. Even though the impact categories assess might be of regional or global scale, the study only assess the impact related to the specific system, while possible ripple effects are excluded. As shipping transporting 80% of the volume of goods in the world, it would be very interesting to asses how major shifts in the fuel choices and consumption level would affect the overall environmental impact of a region. The access of the assessed fuel alternatives has neither been assessed. As the market price is result of demand and supply, it should be assessed how a shift from fossil fuels to biofuels would affect the market of biofuels and food, as the food production is highly integrated with the energy market. To integrate the process based LCA with a IO-analysis could be a way to assess the environmental impact of shipping in a regional or global scale. Hybrid-LCA was earlier presented and discusses in Chapter 4.

7.3.4 DATA QUALITY AND SUGGESTIONS FOR FUTURE STUDIES

The quality of the LCIA is a result of the data applied in the LCI. The uncertainty of the study's results are primarily related to data quality of the processes and flows included and the made assumptions.

The LCIA does reveal which processes and stressors that are the main contributors to the overall impact potentials. Even if rough assumptions have been made for specific processes, the associated impact might have a negligible effect to the overall result of the system. The evaluation of data quality should therefore focus on the decisive factors found in the LCIA.

It has been the aim of the study to apply engine specific data on fuel consumption and emission factors. Unfortunately, this have been found difficult as the literature on use of biofuels for marine applications has been very limited. The biofuel emission factors have therefore to great extent been based upon assumptions. The emissions included for biofuels have been limited to biogenic CO_2, NO_X and PM. An inclusion of other pollutants as CO and NMVOC are desired in future studies.

The fact that the ship operation has proven to be the most important process along the life cycle for several impact categories for the various fuels choices, it is undoubtedly room for improvements by gaining access to direct measurements of emission factors for all fuel alternatives.

In terms of fuel characteristics, such as lower heating value and carbon content, these numbers are believed to be representative.

In this study, WTT-data has to a large extent been based upon the Ecoinvent 2.2 database. Unfortunately, the brand new Ecoinvent 3.0 database was not available in time to be included in the study. A large section of the database has been updated or expanded. It has been in the study's interest to use updated inventory data. However, possible change in results by applying Ecoinvent 3.0 would commonly be related to changes made in allocation approach and updates in transport distances, Ecoinvent (2013). It is therefore not believed that the new database would lead to significant changes to the studies' results. However, the data on biofuel production from synthetic gas is based on the reference year 2004. Even if the Ecoinvent database has not been updated notably on this topic, it is most desired to use updated data in further studies to assess the impact of current production technologies.

The greatest uncertainly is related to the modeling of the biofuel production, where the literature has been limited. The Ecoinvent states in their report that uncertainty is related to the their unit processes methanol synthesis from syngas. *The biomethanol process suffers from the fact that the technology is not yet mature and is not studied as extensively as other biofuels (e.g. biodiesel, bioethanol) in terms of life cycle analyses*, Jungbluth et al. (2007a). As seen in Table 7.3.1, the GWP result for methanol is varying the most compared to the literature.

Regarding effluents from the DME and FT-diesel production facility, the report by Jungbluth et al. (2007b) states that these data are based on rough assumptions. The emission profile for the two plants are based on literature and has been modified from other plant facilities with similar production processes. Off-gas from the facilities has proven to be a key contributor in terms of PMFP and GWP for the two fuel life cycles. More process specific data would reduce some of the uncertainty attached to these results.

The quality of the study is not only made up by the quality of the data included. It is limited by the inclusion of processes and environmental flows. Cut-offs, i.e incomplete system boundaries, might lead to biased results. This study has proven that biogenic emissions related to biomass storage can have a significant contribution to the overall GWP. This is something that is often left out in LCA studies, and might lead to an underestimation of biofuel's potential impact. The literature on the topic is unfortunately limited, and this study has revealed varying modeling approaches among the LCA studies. Standards for rates, types and quantities of GHG emitted from biomass storage should be applied in order make a fair comparison of different production paths.

The distribution of alternative fuels are a process which has been simplified to a large degree in this study. The inclusion of impacts has elusively been related to the operation of the *transoceanic tanker* from the Ecoinvent database and inclusion of BOG ventilation for the LNG distribution.

The fact that CH_4 is a potent GHG, it is possible that leakages related to bunkering could increase the overall GWP derived for LNG. Rough assumptions were also made regarding the transporting distances applied for LNG distribution. More detailed data on the emissions related to LNG bunkering should be applied in further LCA studies. For the biofuel's life cycle, the fuel transportation was found to not have any significant impact to the emphasized impact categories. Time and labour should therefor be invested in assessing other process along the biofuel life cycle which have proven important to the overall impact potentials.

8

CONCLUSION

The objective of this study has been to develop and illustrate a life-cycle based approach to evaluate the environmental impact of fuel choice for different marine vessels and their typical operations. Throughout the study six research questions have been considered. Key findings and results obtained in this study will now be presented in relation to each research question.

1. **What are the environmental impacts considered important for ships, and pertinent policies and regulations?**

Previous regulations imposed to the marine sector have concentrated on reducing the emissions of NO_X and SO_X, i.e. implementation of Emission Control Areas in order to reduce the fuel's sulphur content and the Tier I-III NOX emission limits which regulates the NO_X emissions of newly and future built ships. Research have found that particulate matter forming emissions, i.e. NO_X and SO_X, from shipping are causing health problems to humans such as heart and lung disorders. The emissions also affect the ecosystems through acid rain and eutrophication.

More recently, as the concern of global warming has grown, new regulations have tried to reduce the fuel consumption by improving the design efficiency of ships and promote energy management in the marine sector by imposing the mandatory Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships.

1. **What are the findings of the current literature on the life-cycle impacts and climate effects of ships? What is the contribution of different life cycle stages?**

The few published environmental assessments of ships with a life-cycle based approach have concentrated on assessing the emissions of CO_2, SO_2 and NO_X related to use of conventional marine fuels. The literature on biofuels applied for the marine sector is limited, and has mainly concentrated on first-generation biofuels such as palm oil and rape seed oil.

The literature finds the ship operation responsible for around 90% of the assessed emissions along the life cycle of conventional fuels. For biofuels the share of impact generated by the WTT-phase was of greater magnitude. The results did not un-ambiguously state that switching into biofuels will decrease the environmental impact. Compared to conventional fuels, biofuels are found to reduce the GWP, but generates a greater eutrophication potential.

The results obtained in this study confirms fuel combustion as the main contributing phase along the life cycle of fossil fuels, regarding GWP and PMFP. The processes upstream to the ship operation tend to have a larger contribution to the GWP for the biofuels, compared to fossil fuels. The impact potential was mainly related to the production stages as use of fertilizers, transportation, energy use and production emissions. The results has shown that other environmental impact categories are primarily related to resource extraction, such as ALOP.

3. **How can less-important life cycle stages be included in a similar manner in order to simplify the assessment of different ship types?**

The scope of the study comprising the life cycle of the fuel alternatives, from a cradle-to-grave perspective. The construction, maintenance and demolition of the vessels applying these fuels have therefore been excluded. This study has utilized life cycle inventory databases to model the construction of fuel production facilities and the distribution of the fuels.

4. **How can knowledge on energy efficiency and combustion-related emissions of ship motors, dependent on operations, the type of ship and engine, and the fuel, be included in the assessment?**

The life cycle of the alternative fuels has been modeled as a system with processes, input-, output and intermediate flows. Each life cycle stage, from resource extraction, fuel production and distribution to fuel combustion has been modeled as individual processes. Each flow is bound to the characteristics of the process. For example has the flow of substances to the environment during fuel combustion under different operational stages been set by the fuel type and engine characteristics. The amount of fuel from storage demanded by the ship operation is decided by the specific fuel consumption for each operational phase. All process flows in the system relate to the system's functional unit, which enables comparison of the different life cycles as functionally equivalent systems.

5. **Is there a trade-off between multiple environmental impacts? What are the factors that might influence the preferred fuel for vessels?**

The LCIA has shown that the introduction of biofuels may not only have positive effects on the environment. Introduction of biofuels has resulted in significant reduction of impact potentials considered important by the international maritime community, i.e. climate change and particulate matter formation. However, use of biofuels generate a significant higher impact to the environment when considering other impact categories such as agricultural land occupation.

The results show a highly fluctuating ALOP regarding the type of cellulosic material applied for biofuel production. The impact potential can be drastically reduced by using a suitable feedstock, such as short-rotation wood, and by promoting efficient resource use. The GWP results have shown sensitive towards the modeling choices of emissions from biomass storage, which is responsible for 34.5% of the generated GWP alone the life cycle of methanol, to the inclusion of climate impact of biogenic carbon emissions.

LNG was found to be the far most promising fuel alternative considering PMFP, but an introduction of LNG will not lead to a significant change in GWP. LNG should therefore be applied to ships which operates in coastal areas that are severely loaded with particular matter in air in order to improve the local and regional air quality.

6. **What are the most promising low-carbon fuel alternatives for marine application?**

The LCIA conducted in this study confirms many of the earlier presented arguments for introducing alternative fuels in shipping, i.e. lower PMFP and GWP. However, the results show that various impact categories must be considered before promoting alternative fuels, as the results for each impact category are ambiguous.

Considering particulate matter formation, it was found that fuels with low sulphur content in general achieve a reduction of PMFP, i.e MDO/MGO, LNG and biofuels. For the alternative fuels, NO_X was the main contributing stressor of PMFP, which can be related to the negligible sulfur content. For the conventional fuels, both PM and SO_X emissions were of significant importance in addition to NO_X emissions.

Compared to HFO, use of LNG by the RoPax ferry resulted in a 7.0% decrease in GWP, while the GWP was increased by 1.9% when the fuel was applied for the container ship. The results show a significant reduction of GWP when substituting HFO with biofuels when biogenic CO_2 emissions are considered climate neutral. Use of methanol resulted in a decrease in GWP of approximately 56%, while the reduction for DME and FT-diesel equaled to around 80% and 78%, respectively. Emissions of CO_2 was found to be the main contributor to GWP along the life cycle of fossil fuels, while CH_4 and N_2O also contributes to a significant share of the GWP of biofuels.

Considering the three impact categories emphasized in this study, Fisher Tropsch-diesel and Dimethyl Ether appear as the most promising fuel alternatives for marine application. However, future studies which can provide more specific data on the life cycle of biofuels, are highly encouraged. More research on the combustion of biofuels by marine engines and feedstock extraction should be prioritized in order to level the quality of LCA studies on marine fuel alternatives.

9

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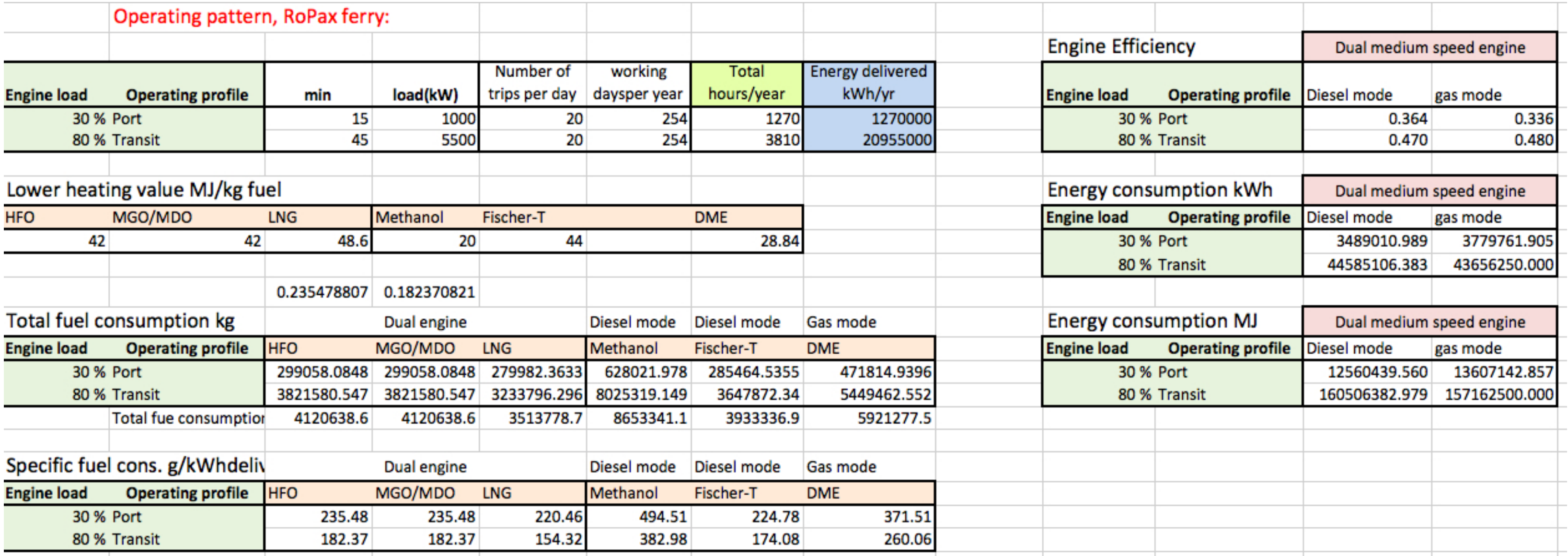
10

APPENDIX

10.1 LCI

10.1.1 OPERATIONAL PATTERNS AND FUEL CONSUMPTION

Table 10.1.1: Operating pattern, RoPax ferry



Operating pattern, RoPax ferry:

Engine load	Operating profile	min	load(kW)	Number of trips per day	working daysper year	Total hours/year	Energy delivered kWh/yr
30 %	Port	15	1000	20	254	1270	1270000
80 %	Transit	45	5500	20	254	3810	20955000

Lower heating value MJ/kg fuel

HFO	MGO/MDO	LNG	Methanol	Fischer-T		DME
42	42	48.6	20	44		28.84
		0.235478807	0.182370821			

Total fuel consumption kg

			Dual engine		Diesel mode	Diesel mode	Gas mode
Engine load	Operating profile	HFO	MGO/MDO	LNG	Methanol	Fischer-T	DME
30 %	Port	299058.0848	299058.0848	279982.3633	628021.978	285464.5355	471814.9396
80 %	Transit	3821580.547	3821580.547	3233796.296	8025319.149	3647872.34	5449462.552
	Total fue consumptior	4120638.6	4120638.6	3513778.7	8653341.1	3933336.9	5921277.5

Specific fuel cons. g/kWhdeli

			Dual engine		Diesel mode	Diesel mode	Gas mode
Engine load	Operating profile	HFO	MGO/MDO	LNG	Methanol	Fischer-T	DME
30 %	Port	235.48	235.48	220.46	494.51	224.78	371.51
80 %	Transit	182.37	182.37	154.32	382.98	174.08	260.06

Engine Efficiency

		Dual medium speed engine	
Engine load	Operating profile	Diesel mode	gas mode
30 %	Port	0.364	0.336
80 %	Transit	0.470	0.480

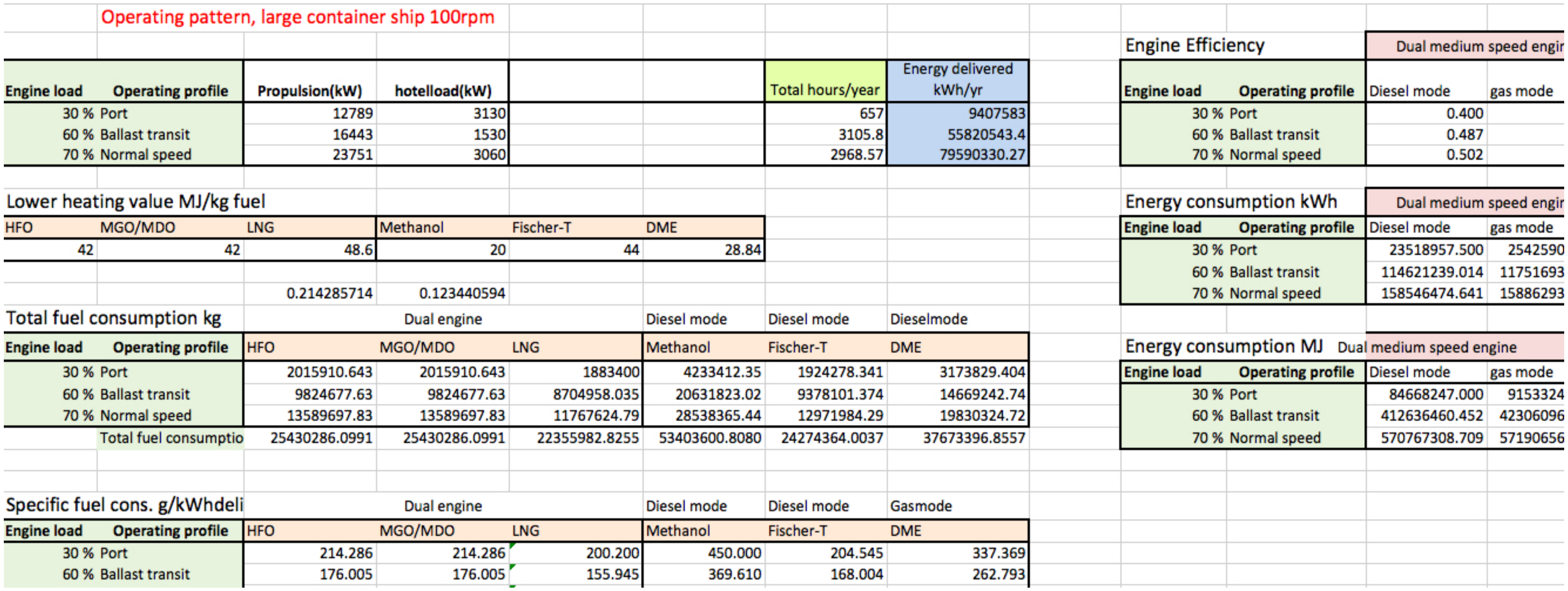
Energy consumption kWh

		Dual medium speed engine	
Engine load	Operating profile	Diesel mode	gas mode
30 %	Port	3489010.989	3779761.905
80 %	Transit	44585106.383	43656250.000

Energy consumption MJ

		Dual medium speed engine	
Engine load	Operating profile	Diesel mode	gas mode
30 %	Port	12560439.560	13607142.857
80 %	Transit	160506382.979	157162500.000

Table 10.1.2: Operating pattern, container ship



Operating pattern, large container ship 100rpm

Engine load	Operating profile	Propulsion(kW)	hotelload(kW)	Total hours/year	Energy delivered kWh/yr
30 %	Port	12789	3130	657	9407583
60 %	Ballast transit	16443	1530	3105.8	55820543.4
70 %	Normal speed	23751	3060	2968.57	79590330.27

Lower heating value MJ/kg fuel

HFO	MGO/MDO	LNG	Methanol	Fischer-T	DME
42	42	48.6	20	44	28.84
		0.214285714	0.123440594		

Total fuel consumption kg

			Dual engine		Diesel mode	Diesel mode	Dieselmode
Engine load	Operating profile	HFO	MGO/MDO	LNG	Methanol	Fischer-T	DME
30 %	Port	2015910.643	2015910.643	1883400	4233412.35	1924278.341	3173829.404
60 %	Ballast transit	9824677.63	9824677.63	8704958.035	20631823.02	9378101.374	14669242.74
70 %	Normal speed	13589697.83	13589697.83	11767624.79	28538365.44	12971984.29	19830324.72
	Total fuel consumptio	25430286.0991	25430286.0991	22355982.8255	53403600.8080	24274364.0037	37673396.8557

Specific fuel cons. g/kWhdeli

			Dual engine		Diesel mode	Diesel mode	Gasmode
Engine load	Operating profile	HFO	MGO/MDO	LNG	Methanol	Fischer-T	DME
30 %	Port	214.286	214.286	200.200	450.000	204.545	337.369
60 %	Ballast transit	176.005	176.005	155.945	369.610	168.004	262.793

Engine Efficiency

		Dual medium speed engir	
Engine load	Operating profile	Diesel mode	gas mode
30 %	Port	0.400	
60 %	Ballast transit	0.487	
70 %	Normal speed	0.502	

Energy consumption kWh

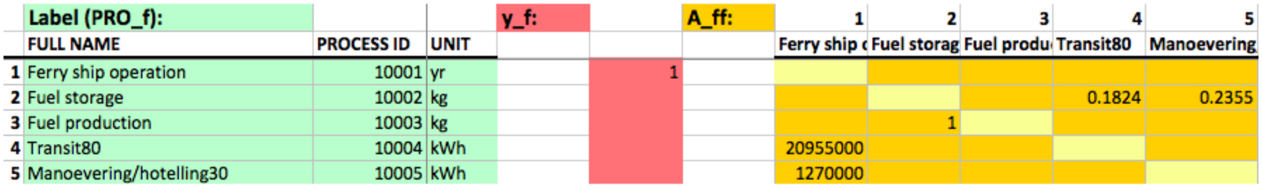
		Dual medium speed engir	
Engine load	Operating profile	Diesel mode	gas mode
30 %	Port	23518957.500	2542590
60 %	Ballast transit	114621239.014	11751693
70 %	Normal speed	158546474.641	15886293

Energy consumption MJ

		Dual medium speed engine	
Engine load	Operating profile	Diesel mode	gas mode
30 %	Port	84668247.000	9153324
60 %	Ballast transit	412636460.452	42306096
70 %	Normal speed	570767308.709	57190656

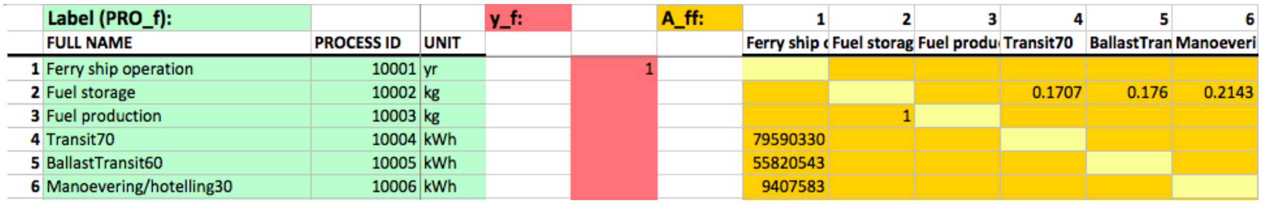
10.1.2 FOREGROUND MATRIXES

Table 10.1.3: HFO/MDO/MGO, foreground matrix, RoPax ferry



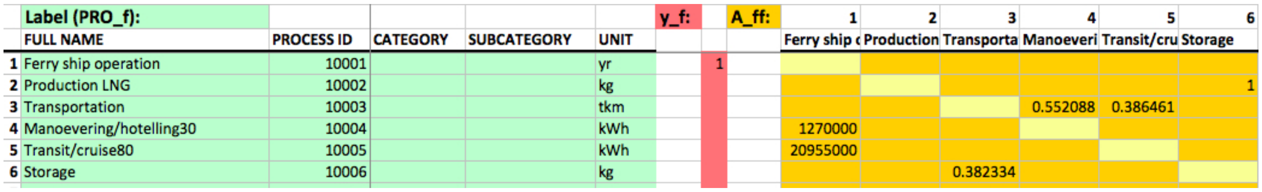
	Label (PRO_f):			y_f:		A_ff:	1	2	3	4	5
	FULL NAME	PROCESS ID	UNIT				Ferry ship	Fuel storag	Fuel produ	Transit80	Manoevering
1	Ferry ship operation	10001	yr		1						
2	Fuel storage	10002	kg							0.1824	0.2355
3	Fuel production	10003	kg					1			
4	Transit80	10004	kWh				20955000				
5	Manoevering/hotelling30	10005	kWh				1270000				

Table 10.1.4: HFO/MDO/MGO, foreground matrix, container ship



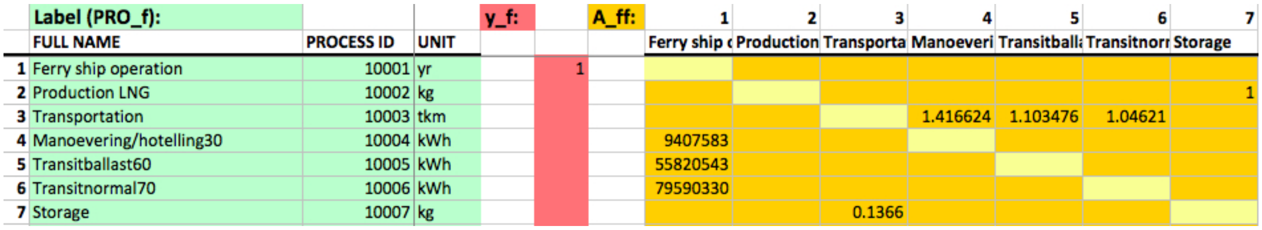
	Label (PRO_f):			y_f:		A_ff:	1	2	3	4	5	6
	FULL NAME	PROCESS ID	UNIT				Ferry ship	Fuel storag	Fuel produ	Transit70	BallastTran	Manoeveri
1	Ferry ship operation	10001	yr		1							
2	Fuel storage	10002	kg							0.1707	0.176	0.2143
3	Fuel production	10003	kg					1				
4	Transit70	10004	kWh				79590330					
5	BallastTransit60	10005	kWh				55820543					
6	Manoevering/hotelling30	10006	kWh				9407583					

Table 10.1.5: LNG, foreground matrix, RoPax ferry



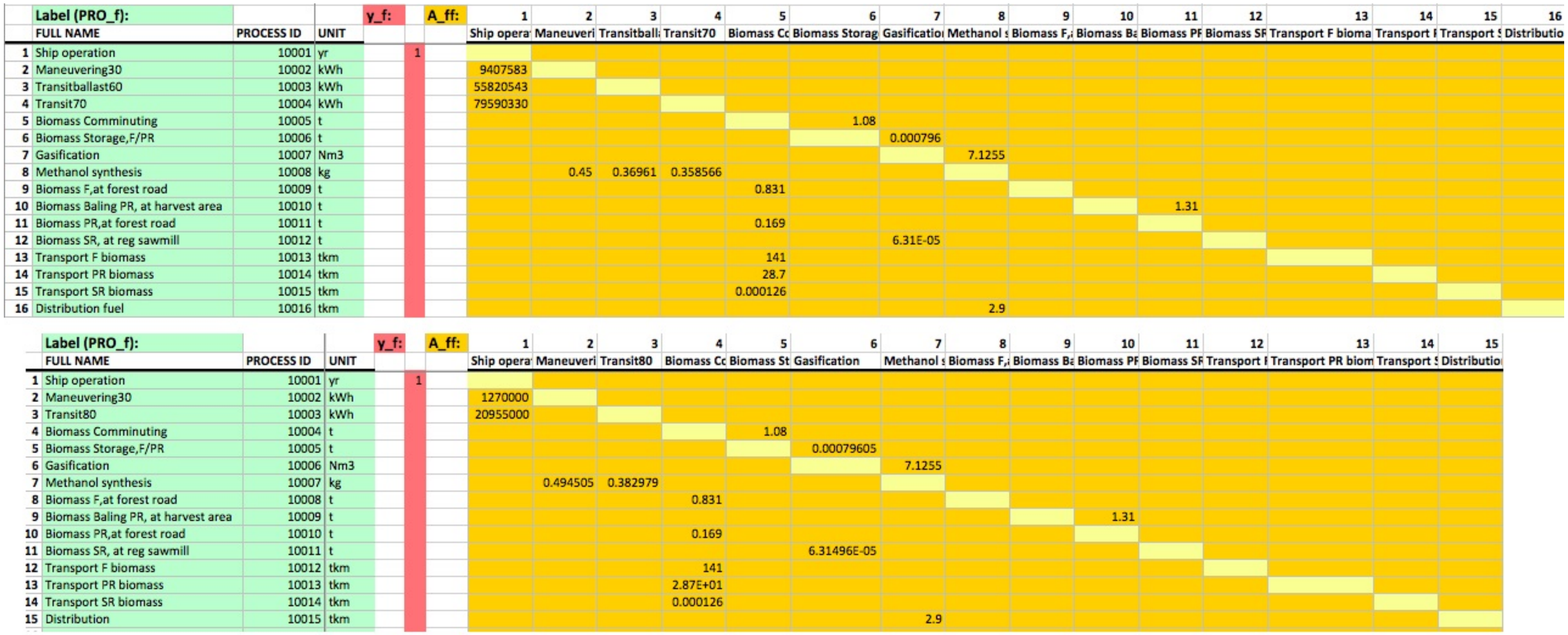
	Label (PRO_f):					**y_f:**		**A_ff:**	**1**	**2**	**3**	**4**	**5**	**6**
	FULL NAME	**PROCESS ID**	**CATEGORY**	**SUBCATEGORY**	**UNIT**				**Ferry ship**	**Production**	**Transporta**	**Manoeveri**	**Transit/cru**	**Storage**
1	Ferry ship operation	10001			yr		1							
2	Production LNG	10002			kg									1
3	Transportation	10003			tkm							0.552088	0.386461	
4	Manoevering/hotelling30	10004			kWh				1270000					
5	Transit/cruise80	10005			kWh				20955000					
6	Storage	10006			kg						0.382334			

Table 10.1.6: LNG, foreground matrix, container ship



	Label (PRO_f):			**y_f:**		**A_ff:**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
	FULL NAME	**PROCESS ID**	**UNIT**				**Ferry ship**	**Production**	**Transporta**	**Manoeveri**	**Transitball**	**Transitnor**	**Storage**
1	Ferry ship operation	10001	yr		1								
2	Production LNG	10002	kg										1
3	Transportation	10003	tkm							1.416624	1.103476	1.04621	
4	Manoevering/hotelling30	10004	kWh				9407583						
5	Transitballast60	10005	kWh				55820543						
6	Transitnormal70	10006	kWh				79590330						
7	Storage	10007	kg						0.1366				

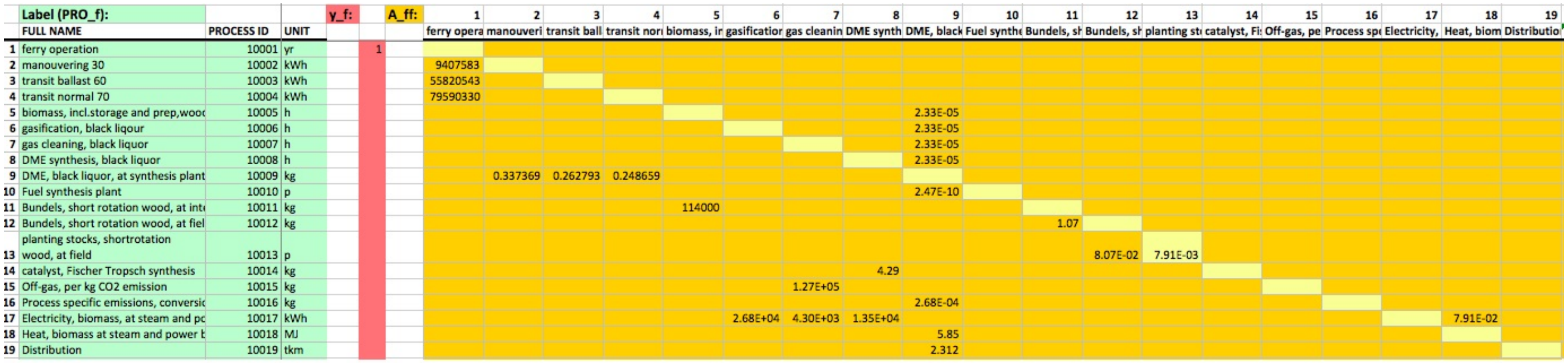
Table 10.1.7: Methanol, foreground matrix, container ship and RoPax ferry



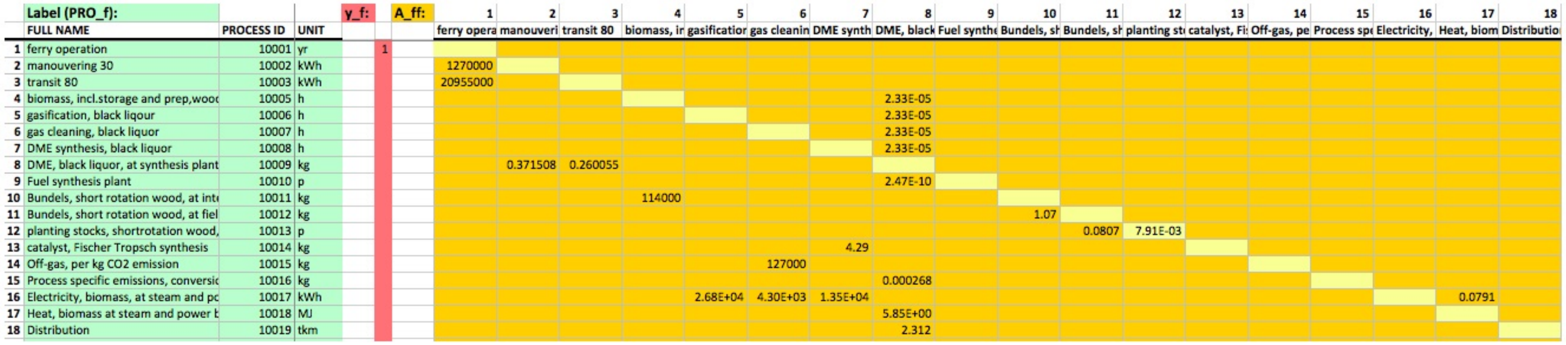
	Label (PRO_f):			y_f:	A_ff:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	FULL NAME	PROCESS ID	UNIT			Ship opera	Maneuveri	Transitball	Transit70	Biomass C	Biomass Storag	Gasificatio	Methanol	Biomass F,	Biomass B	Biomass P	Biomass S	Transport F bioma	Transport	Transport	Distributio
1	Ship operation	10001	yr	1																	
2	Maneuvering30	10002	kWh			9407583															
3	Transitballast60	10003	kWh			55820543															
4	Transit70	10004	kWh			79590330															
5	Biomass Comminuting	10005	t								1.08										
6	Biomass Storage,F/PR	10006	t									0.000796									
7	Gasification	10007	Nm3										7.1255								
8	Methanol synthesis	10008	kg				0.45	0.36961	0.358566												
9	Biomass F,at forest road	10009	t							0.831											
10	Biomass Baling PR, at harvest area	10010	t													1.31					
11	Biomass PR,at forest road	10011	t							0.169											
12	Biomass SR, at reg sawmill	10012	t									6.31E-05									
13	Transport F biomass	10013	tkm							141											
14	Transport PR biomass	10014	tkm							28.7											
15	Transport SR biomass	10015	tkm							0.000126											
16	Distribution fuel	10016	tkm										2.9								

	Label (PRO_f):			y_f:	A_ff:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	FULL NAME	PROCESS ID	UNIT			Ship opera	Maneuveri	Transit80	Biomass C	Biomass St	Gasification	Methanol	Biomass F,	Biomass B	Biomass P	Biomass S	Transport	Transport PR biom	Transport	Distributio
1	Ship operation	10001	yr	1																
2	Maneuvering30	10002	kWh			1270000														
3	Transit80	10003	kWh			20955000														
4	Biomass Comminuting	10004	t							1.08										
5	Biomass Storage,F/PR	10005	t								0.00079605									
6	Gasification	10006	Nm3									7.1255								
7	Methanol synthesis	10007	kg				0.494505	0.382979												
8	Biomass F,at forest road	10008	t						0.831											
9	Biomass Baling PR, at harvest area	10009	t												1.31					
10	Biomass PR,at forest road	10010	t						0.169											
11	Biomass SR, at reg sawmill	10011	t								6.31496E-05									
12	Transport F biomass	10012	tkm						141											
13	Transport PR biomass	10013	tkm						2.87E+01											
14	Transport SR biomass	10014	tkm						0.000126											
15	Distribution	10015	tkm									2.9								

Table 10.1.8: DME, foreground matrix, container ship and RoPax ferry

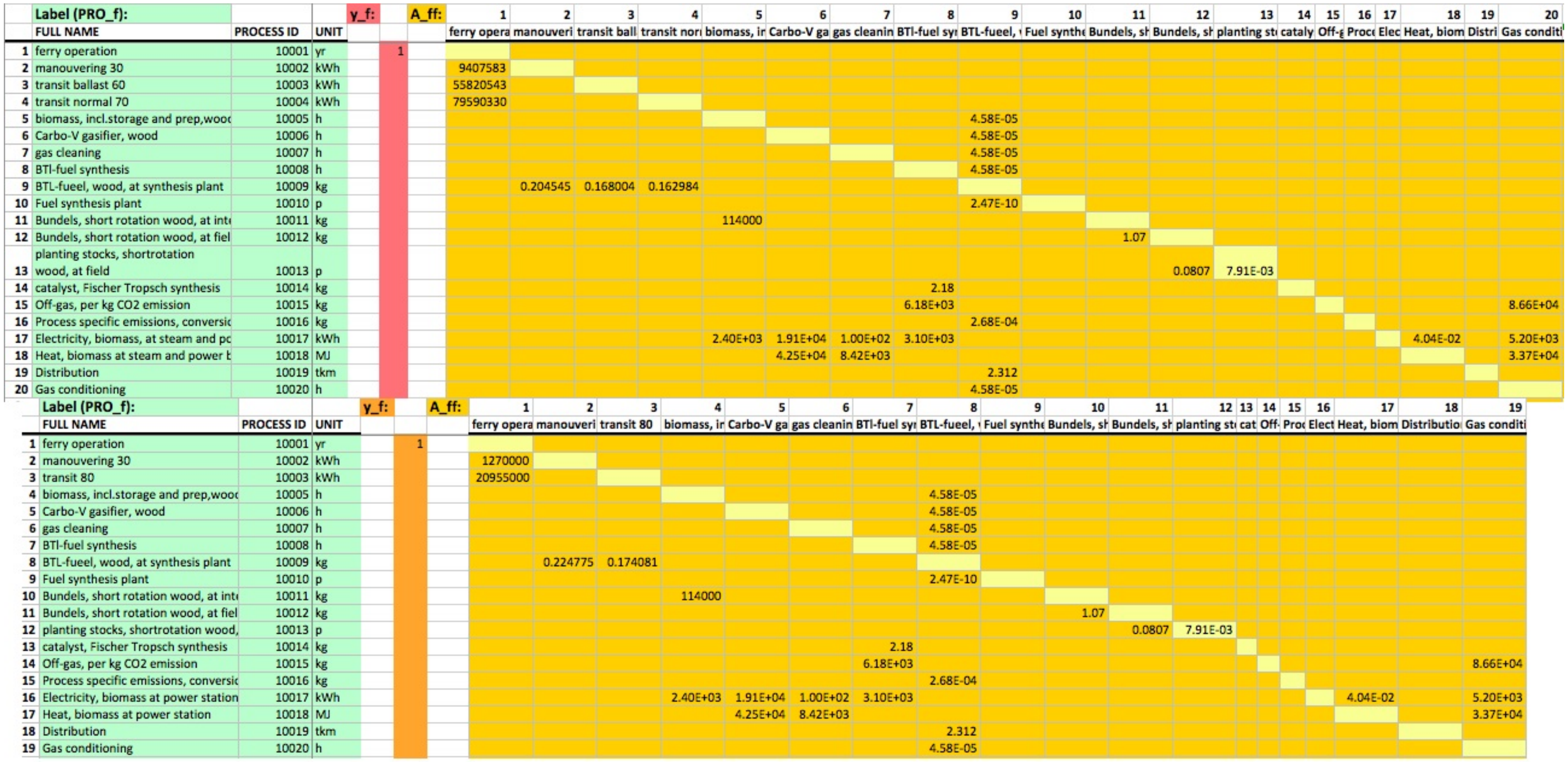


	Label (PRO_f):			y_f:		A_ff:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
	FULL NAME	PROCESS ID	UNIT				ferry opera	manouveri	transit ball	transit nori	biomass, ir	gasificatior	gas cleanin	DME synth	DME, black	Fuel synthe	Bundels, sh	Bundels, sh	planting st	catalyst, Fi:	Off-gas, pe	Process spe	Electricity,	Heat, biom	Distributio
1	ferry operation	10001	yr		1																				
2	manouvering 30	10002	kWh				9407583																		
3	transit ballast 60	10003	kWh				55820543																		
4	transit normal 70	10004	kWh				79590330																		
5	biomass, incl.storage and prep,wooc	10005	h												2.33E-05										
6	gasification, black liqour	10006	h												2.33E-05										
7	gas cleaning, black liquor	10007	h												2.33E-05										
8	DME synthesis, black liquor	10008	h												2.33E-05										
9	DME, black liquor, at synthesis plant	10009	kg					0.337369	0.262793	0.248659															
10	Fuel synthesis plant	10010	p												2.47E-10										
11	Bundels, short rotation wood, at inte	10011	kg								114000														
12	Bundels, short rotation wood, at fiel	10012	kg														1.07								
13	planting stocks, shortrotation wood, at field	10013	p															8.07E-02	7.91E-03						
14	catalyst, Fischer Tropsch synthesis	10014	kg											4.29											
15	Off-gas, per kg CO2 emission	10015	kg										1.27E+05												
16	Process specific emissions, conversic	10016	kg												2.68E-04										
17	Electricity, biomass, at steam and pc	10017	kWh									2.68E+04	4.30E+03	1.35E+04										7.91E-02	
18	Heat, biomass at steam and power k	10018	MJ												5.85										
19	Distribution	10019	tkm												2.312										



	Label (PRO_f):			y_f:		A_ff:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	FULL NAME	PROCESS ID	UNIT				ferry opera	manouveri	transit 80	biomass, ir	gasificatior	gas cleanin	DME synth	DME, black	Fuel synthe	Bundels, sh	Bundels, sh	planting st	catalyst, Fi:	Off-gas, pe	Process spe	Electricity,	Heat, biom	Distributio
1	ferry operation	10001	yr		1																			
2	manouvering 30	10002	kWh				1270000																	
3	transit 80	10003	kWh				20955000																	
4	biomass, incl.storage and prep,wooc	10005	h											2.33E-05										
5	gasification, black liqour	10006	h											2.33E-05										
6	gas cleaning, black liquor	10007	h											2.33E-05										
7	DME synthesis, black liquor	10008	h											2.33E-05										
8	DME, black liquor, at synthesis plant	10009	kg					0.371508	0.260055															
9	Fuel synthesis plant	10010	p											2.47E-10										
10	Bundels, short rotation wood, at inte	10011	kg							114000														
11	Bundels, short rotation wood, at fiel	10012	kg													1.07								
12	planting stocks, shortrotation wood,	10013	p														0.0807	7.91E-03						
13	catalyst, Fischer Tropsch synthesis	10014	kg										4.29											
14	Off-gas, per kg CO2 emission	10015	kg									127000												
15	Process specific emissions, conversic	10016	kg											0.000268										
16	Electricity, biomass, at steam and pc	10017	kWh								2.68E+04	4.30E+03	1.35E+04										0.0791	
17	Heat, biomass at steam and power k	10018	MJ											5.85E+00										
18	Distribution	10019	tkm											2.312										

Table 10.1.9: FT-diesel, foreground matrix, container ship and RoPax ferry



	Label (PRO_f):			y_f:		A_ff:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	FULL NAME	PROCESS ID	UNIT				ferry opera	manouveri	transit ball	transit nor	biomass, ir	Carbo-V ga	gas cleanin	BTl-fuel sy	BTL-fueel,	Fuel synthe	Bundels, sh	Bundels, sh	planting st	cataly	Off-g	Proc	Elec	Heat, biom	Distri	Gas conditi
1	ferry operation	10001	yr		1																					
2	manouvering 30	10002	kWh				9407583																			
3	transit ballast 60	10003	kWh				55820543																			
4	transit normal 70	10004	kWh				79590330																			
5	biomass, incl.storage and prep,wooc	10005	h												4.58E-05											
6	Carbo-V gasifier, wood	10006	h												4.58E-05											
7	gas cleaning	10007	h												4.58E-05											
8	BTl-fuel synthesis	10008	h												4.58E-05											
9	BTL-fueel, wood, at synthesis plant	10009	kg					0.204545	0.168004	0.162984																
10	Fuel synthesis plant	10010	p												2.47E-10											
11	Bundels, short rotation wood, at int	10011	kg								114000															
12	Bundels, short rotation wood, at fiel	10012	kg														1.07									
13	planting stocks, shortrotation wood, at field	10013	p															0.0807	7.91E-03							
14	catalyst, Fischer Tropsch synthesis	10014	kg											2.18												
15	Off-gas, per kg CO2 emission	10015	kg											6.18E+03												8.66E+04
16	Process specific emissions, conversic	10016	kg												2.68E-04											
17	Electricity, biomass, at steam and pc	10017	kWh								2.40E+03	1.91E+04	1.00E+02	3.10E+03										4.04E-02		5.20E+03
18	Heat, biomass at steam and power b	10018	MJ									4.25E+04	8.42E+03													3.37E+04
19	Distribution	10019	tkm												2.312											
20	Gas conditioning	10020	h												4.58E-05											

	Label (PRO_f):			y_f:		A_ff:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
	FULL NAME	PROCESS ID	UNIT				ferry opera	manouveri	transit 80	biomass, ir	Carbo-V ga	gas cleanin	BTl-fuel sy	BTL-fueel,	Fuel synthe	Bundels, sh	Bundels, sh	planting st	cat	Off-	Proc	Elect	Heat, biom	Distributio	Gas conditi
1	ferry operation	10001	yr		1																				
2	manouvering 30	10002	kWh				1270000																		
3	transit 80	10003	kWh				20955000																		
4	biomass, incl.storage and prep,wooc	10005	h											4.58E-05											
5	Carbo-V gasifier, wood	10006	h											4.58E-05											
6	gas cleaning	10007	h											4.58E-05											
7	BTl-fuel synthesis	10008	h											4.58E-05											
8	BTL-fueel, wood, at synthesis plant	10009	kg					0.224775	0.174081																
9	Fuel synthesis plant	10010	p											2.47E-10											
10	Bundels, short rotation wood, at int	10011	kg							114000															
11	Bundels, short rotation wood, at fiel	10012	kg													1.07									
12	planting stocks, shortrotation wood,	10013	p														0.0807	7.91E-03							
13	catalyst, Fischer Tropsch synthesis	10014	kg										2.18												
14	Off-gas, per kg CO2 emission	10015	kg										6.18E+03												8.66E+04
15	Process specific emissions, conversic	10016	kg											2.68E-04											
16	Electricity, biomass at power station	10017	kWh							2.40E+03	1.91E+04	1.00E+02	3.10E+03										4.04E-02		5.20E+03
17	Heat, biomass at power station	10018	MJ								4.25E+04	8.42E+03													3.37E+04
18	Distribution	10019	tkm											2.312											
19	Gas conditioning	10020	h											4.58E-05											

10.1.3 LNG

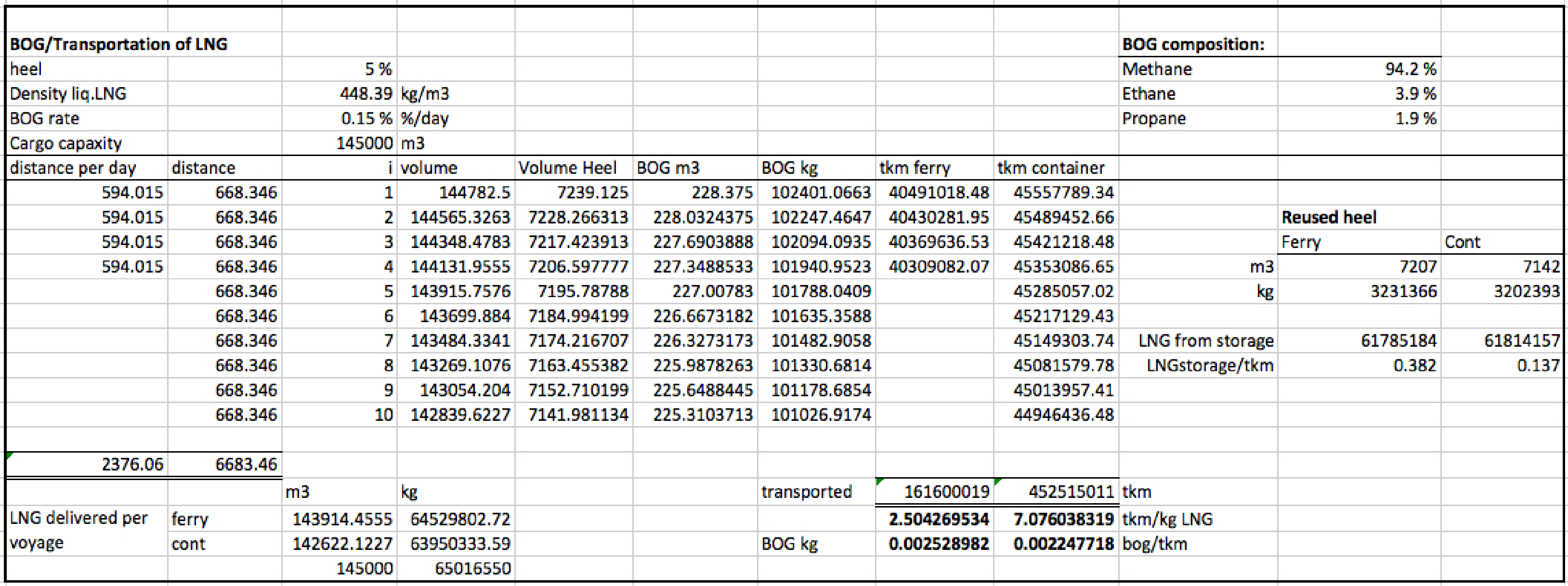
Table 10.1.10: Allocation LNG

Product	Annual production (2011) [t/yr]	LHV [MJ/kg]	Energy Content [GJ]	Allocation factor %
LNG	3,150,000	48.6	153,090,000	0.822
LPG	210,000	46.5	9,765,000	0.052
Condensate	520,000	44.9	23,348,000	0.125

Table 10.1.11: Composition of LNG, vapour phase, % mol, at $-162°C$

Substance	Chemical	% Mol
Methane	CH_4	94.19
Ethane	C_2H_6	3.93
Nitrogen	N	0.75
Propane	C_3H_8	0.61
Isobuthane	C_4H_{10}	0.33
Normalbutane	C_4H_{10}	0.15
Isopenthane	C_5H_{12}	0.04

Table 10.1.12: LNG distribution, calculations



BOG/Transportation of LNG									**BOG composition:**		
heel		5 %							Methane	94.2 %	
Density liq.LNG		448.39	kg/m3						Ethane	3.9 %	
BOG rate		0.15 %	%/day						Propane	1.9 %	
Cargo capaxity		145000	m3								
distance per day	distance	i	volume	Volume Heel	BOG m3	BOG kg	tkm ferry	tkm container			
594.015	668.346	1	144782.5	7239.125	228.375	102401.0663	40491018.48	45557789.34			
594.015	668.346	2	144565.3263	7228.266313	228.0324375	102247.4647	40430281.95	45489452.66		**Reused heel**	
594.015	668.346	3	144348.4783	7217.423913	227.6903888	102094.0935	40369636.53	45421218.48		Ferry	Cont
594.015	668.346	4	144131.9555	7206.597777	227.3488533	101940.9523	40309082.07	45353086.65	m3	7207	7142
	668.346	5	143915.7576	7195.78788	227.00783	101788.0409		45285057.02	kg	3231366	3202393
	668.346	6	143699.884	7184.994199	226.6673182	101635.3588		45217129.43			
	668.346	7	143484.3341	7174.216707	226.3273173	101482.9058		45149303.74	LNG from storage	61785184	61814157
	668.346	8	143269.1076	7163.455382	225.9878263	101330.6814		45081579.78	LNGstorage/tkm	0.382	0.137
	668.346	9	143054.204	7152.710199	225.6488445	101178.6854		45013957.41			
	668.346	10	142839.6227	7141.981134	225.3103713	101026.9174		44946436.48			
2376.06	6683.46										
		m3	kg			transported	161600019	452515011	tkm		
LNG delivered per	ferry	143914.4555	64529802.72				**2.504269534**	**7.076038319**	tkm/kg LNG		
voyage	cont	142622.1227	63950333.59			BOG kg	**0.002528982**	**0.002247718**	bog/tkm		
		145000	65016550								

10.1.4 METHANOL

Calculation of emission factors of biomass storage for methanol production: Methane and nitrous oxide emissions are based on the original nitrogen and carbon contents contained in the wood for a case involving expected dry material losses of 15.6%. Methane emission coefficients used were 0.75 dry wt. % of the initial carbon present, and nitrous oxide emissions were calculated based on 0.5 dry wt. % of the initial nitrogen present, Bright and Strømman (2009).

The biomass entering the storage has a water content (u-value) of 75%, and the biomass leaving the storage has a water content of 50%. A linear relationship between the mass loss and water content is assumed. The average dry matter loss can be calculated as follows:

$$AvgDMloss = \frac{1.08t \times 0.25 + 1.00t \times 0.5}{2} = 385kg \tag{10.1.1}$$

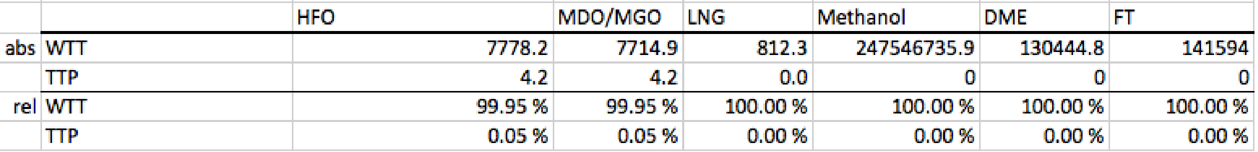
The carbon content equals to 50 dry wt. % and the nitrogen content equals to 0.02 dry wt. % The emission factors per tonne stored biomass equals to:

$$CH_4 = 385kg \times 0.5C/kgDM \times 0.0075 = 1.44kg \tag{10.1.2}$$

$$N_2O = 385kg \times 0.02N/kgDM \times 0.005 = 0.0385kg \tag{10.1.3}$$

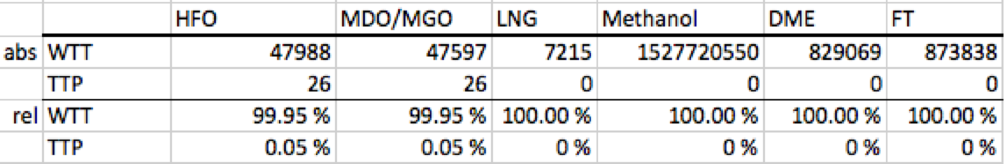
10.2 RESULTS

Table 10.2.1: ALOP per functional unit, RoPax ferry



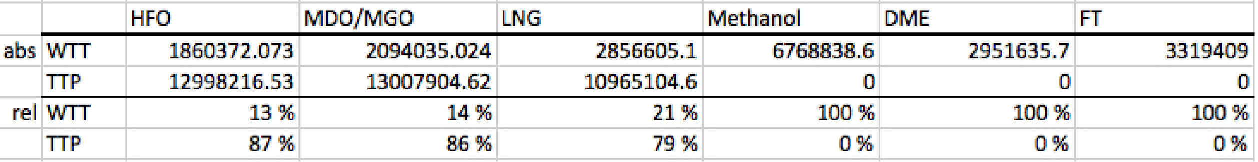
		HFO	MDO/MGO	LNG	Methanol	DME	FT
abs	WTT	7778.2	7714.9	812.3	247546735.9	130444.8	141594
	TTP	4.2	4.2	0.0	0	0	0
rel	WTT	99.95 %	99.95 %	100.00 %	100.00 %	100.00 %	100.00 %
	TTP	0.05 %	0.05 %	0.00 %	0.00 %	0.00 %	0.00 %

Table 10.2.2: ALOP per functional unit, container ship



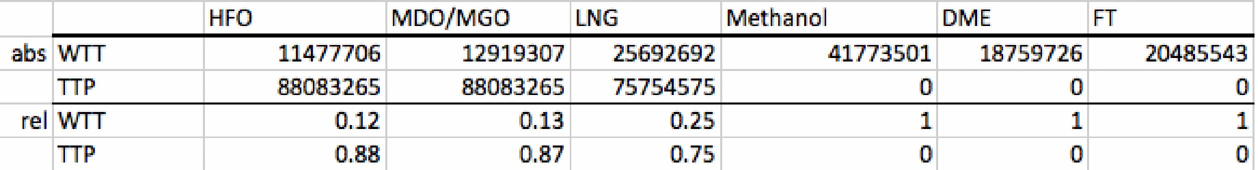
		HFO	MDO/MGO	LNG	Methanol	DME	FT
abs	WTT	47988	47597	7215	1527720550	829069	873838
	TTP	26	26	0	0	0	0
rel	WTT	99.95 %	99.95 %	100.00 %	100.00 %	100.00 %	100.00 %
	TTP	0.05 %	0.05 %	0 %	0 %	0 %	0 %

Table 10.2.3: GWP per functional unit, RoPax ferry



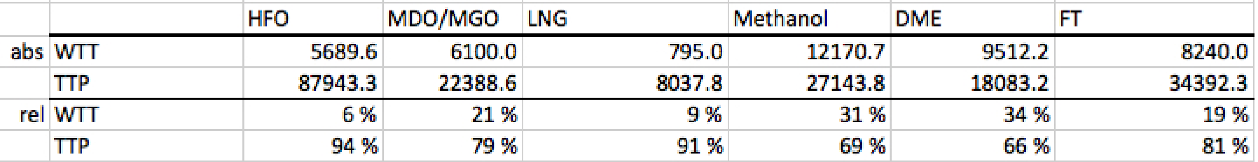
		HFO	MDO/MGO	LNG	Methanol	DME	FT
abs	WTT	1860372.073	2094035.024	2856605.1	6768838.6	2951635.7	3319409
	TTP	12998216.53	13007904.62	10965104.6	0	0	0
rel	WTT	13 %	14 %	21 %	100 %	100 %	100 %
	TTP	87 %	86 %	79 %	0 %	0 %	0 %

Table 10.2.4: GWP per functional unit, container ship



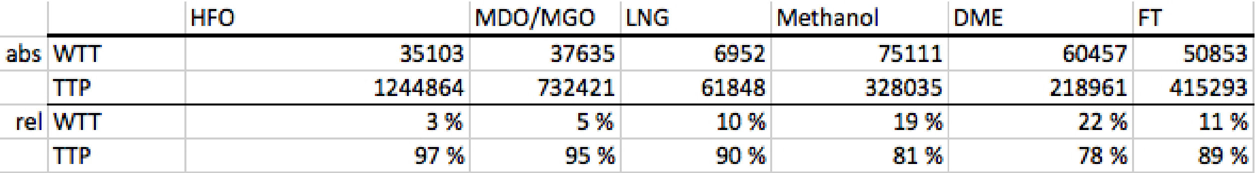
		HFO	MDO/MGO	LNG	Methanol	DME	FT
abs	WTT	11477706	12919307	25692692	41773501	18759726	20485543
	TTP	88083265	88083265	75754575	0	0	0
rel	WTT	0.12	0.13	0.25	1	1	1
	TTP	0.88	0.87	0.75	0	0	0

Table 10.2.5: PMFP per functional unit, RoPax ferry



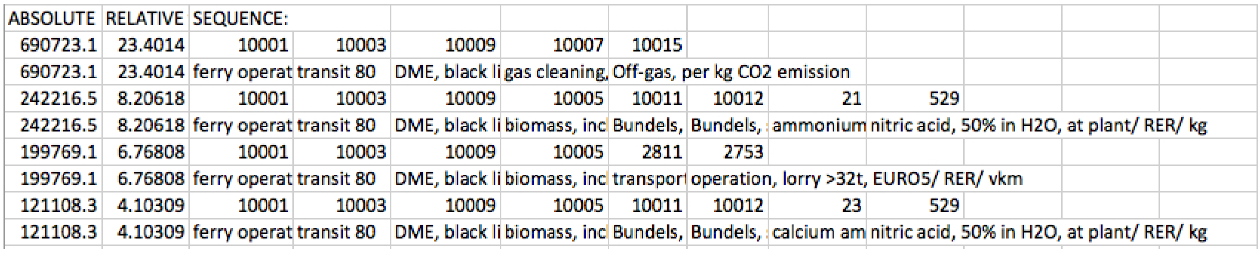
		HFO	MDO/MGO	LNG	Methanol	DME	FT
abs	WTT	5689.6	6100.0	795.0	12170.7	9512.2	8240.0
	TTP	87943.3	22388.6	8037.8	27143.8	18083.2	34392.3
rel	WTT	6 %	21 %	9 %	31 %	34 %	19 %
	TTP	94 %	79 %	91 %	69 %	66 %	81 %

Table 10.2.6: PMFP per functional unit, container ship



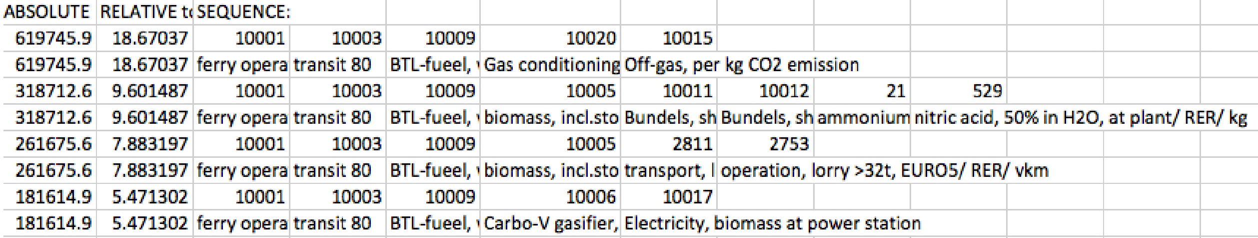
		HFO	MDO/MGO	LNG	Methanol	DME	FT
abs	WTT	35103	37635	6952	75111	60457	50853
	TTP	1244864	732421	61848	328035	218961	415293
rel	WTT	3 %	5 %	10 %	19 %	22 %	11 %
	TTP	97 %	95 %	90 %	81 %	78 %	89 %

Table 10.2.7: GWP, structural path analysis, RoPax ferry, DME



ABSOLUTE	RELATIVE	SEQUENCE:							
690723.1	23.4014	10001	10003	10009	10007	10015			
690723.1	23.4014	ferry operat	transit 80	DME, black li	gas cleaning,	Off-gas, per kg CO2 emission			
242216.5	8.20618	10001	10003	10009	10005	10011	10012	21	529
242216.5	8.20618	ferry operat	transit 80	DME, black li	biomass, inc	Bundels,	Bundels,	ammonium	nitric acid, 50% in H2O, at plant/ RER/ kg
199769.1	6.76808	10001	10003	10009	10005	2811	2753		
199769.1	6.76808	ferry operat	transit 80	DME, black li	biomass, inc	transport	operation, lorry >32t, EURO5/ RER/ vkm		
121108.3	4.10309	10001	10003	10009	10005	10011	10012	23	529
121108.3	4.10309	ferry operat	transit 80	DME, black li	biomass, inc	Bundels,	Bundels,	calcium am	nitric acid, 50% in H2O, at plant/ RER/ kg

Table 10.2.8: GWP, structural path analysis, RoPax ferry, FT-diesel



ABSOLUTE	RELATIVE t	SEQUENCE:							
619745.9	18.67037	10001	10003	10009	10020	10015			
619745.9	18.67037	ferry opera	transit 80	BTL-fueel,	Gas conditioning	Off-gas, per kg CO2 emission			
318712.6	9.601487	10001	10003	10009	10005	10011	10012	21	529
318712.6	9.601487	ferry opera	transit 80	BTL-fueel,	biomass, incl.sto	Bundels, sh	Bundels, sh	ammonium	nitric acid, 50% in H2O, at plant/ RER/ kg
261675.6	7.883197	10001	10003	10009	10005	2811	2753		
261675.6	7.883197	ferry opera	transit 80	BTL-fueel,	biomass, incl.sto	transport, l	operation, lorry >32t, EURO5/ RER/ vkm		
181614.9	5.471302	10001	10003	10009	10006	10017			
181614.9	5.471302	ferry opera	transit 80	BTL-fueel,	Carbo-V gasifier,	Electricity, biomass at power station			

10.3 SENSITIVITY ANALYSIS

10.3.1 BIOMASS STORAGE, DME AND FT-DIESEL

Calculation of emission factors of biomass storage for DME production, Sensitivity Analysis: The used coefficients equals to the ones used for biomass storage in the methanol fuel life cycle chain.

Water content of stored biomass equals to 20%.

$$DMloss = 1.07t \times 0.2 = 214kg \tag{10.3.1}$$

The carbon content equals to 48 dry wt. % and the nitrogen content equals to 0.0049 dry wt. % The emission factors per tonne stored biomass equals to:

$$CH_4 = 214kg \times 0.48C/kgDM \times 0.0075 = 0.7704kg \tag{10.3.2}$$

$$N_2O = 214kg \times 0.0049N/kgDM \times 0.005 = 0.005243kg \tag{10.3.3}$$

Calculation of emission factors of biogenic $\mathbf{CO_2}$ emissions given carbon content:

$$EF_{\mathrm{CO2}=C_{\%}} \times \frac{C_{CO2}}{C_m} = C_{\%} \times \frac{44}{12} \tag{10.3.4}$$

Where:

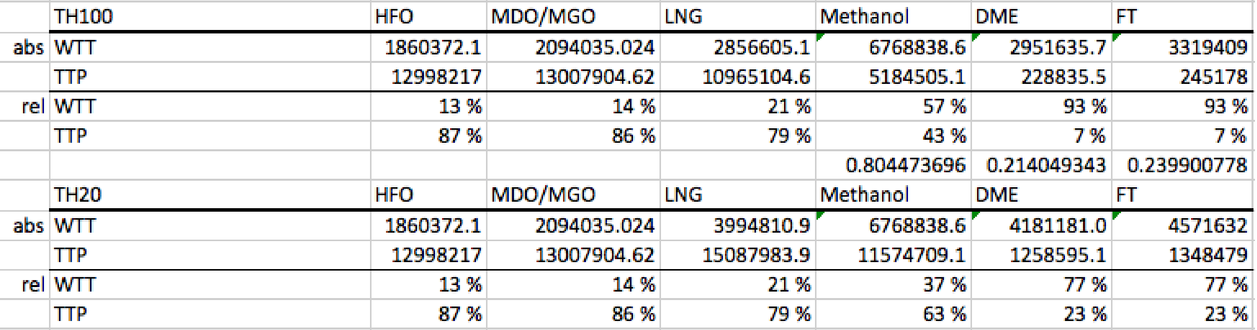
$EF_{\mathrm{CO_2}}$ = Emission factor [kg $\mathrm{CO_2}$/kg fuel]

$C_{\%}$ = Carbon content of fuel [kg C/kg fuel]

C_{CO2} = Molecular weight of $\mathrm{CO_2}$ [44 kg/mol $\mathrm{CO_2}$]

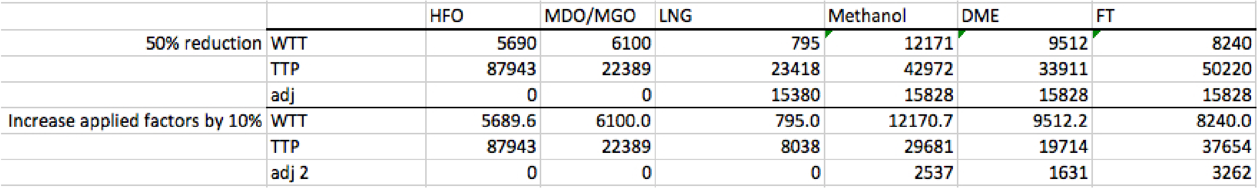
C_{m} = Molecular weight of C [12 kg/mol C]

Table 10.3.1: GWP per functional unit, sensitivity analysis, RoPax Ferry



	TH100	HFO	MDO/MGO	LNG	Methanol	DME	FT
abs	WTT	1860372.1	2094035.024	2856605.1	6768838.6	2951635.7	3319409
	TTP	12998217	13007904.62	10965104.6	5184505.1	228835.5	245178
rel	WTT	13 %	14 %	21 %	57 %	93 %	93 %
	TTP	87 %	86 %	79 %	43 %	7 %	7 %
					0.804473696	0.214049343	0.239900778
	TH20	HFO	MDO/MGO	LNG	Methanol	DME	FT
abs	WTT	1860372.1	2094035.024	3994810.9	6768838.6	4181181.0	4571632
	TTP	12998217	13007904.62	15087983.9	11574709.1	1258595.1	1348479
rel	WTT	13 %	14 %	21 %	37 %	77 %	77 %
	TTP	87 %	86 %	79 %	63 %	23 %	23 %

Table 10.3.2: Relative change in impact potential, resource efficiency adjusted, RoPax ferry



		HFO	MDO/MGO	LNG	Methanol	DME	FT
50% reduction	WTT	5690	6100	795	12171	9512	8240
	TTP	87943	22389	23418	42972	33911	50220
	adj	0	0	15380	15828	15828	15828
Increase applied factors by 10%	WTT	5689.6	6100.0	795.0	12170.7	9512.2	8240.0
	TTP	87943	22389	8038	29681	19714	37654
	adj 2	0	0	0	2537	1631	3262

Table 10.3.3: Relative change in impact potential, resource efficiency adjusted, RoPax ferry

Char.factor	Initial value/f.u.	Adjusted value/f.u	Rel [%]
ALOP	2.48E+08	1.85E+08	74.7
GWP100	6.77E+06	5.15E+06	76.1
FDP	1.30E+06	1.00E+06	77.0
FETPinf	5.70E+04	4.61E+04	80.8
FEP	1.02E+03	8.40E+02	82.2
HTP	4.52E+06	3.45E+06	76.3
IRP	6.17E+05	4.76E+05	77.2
METP	4.81E+04	3.73E+04	77.6
MEP	2.27E+04	2.16E+04	95.3
MDP	2.99E+05	2.47E+05	82.7
NLTP	1.87E+03	1.46E+03	77.7
ODP	9.38E-01	7.11E-01	75.9
PMFP	3.93E+04	3.69E+04	93.8
POFP	4.43E+05	3.62E+05	81.7
TAP100	9.64E+04	9.03E+04	93.6
TETP	7.16E+02	5.94E+02	83.0
ULOP	1.25E+05	9.58E+04	76.4
WDP	2.76E+04	2.32E+04	84.1