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Life Cycle Assessment of Marine Fuel Production

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MASTER THESIS

for

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Life cycle assessment of marine fuel production.

Background and objective

International maritime transport is the backbone of international trade. Though emissions per unit of goods transported are low compared to other transport modes, absolute emissions from the sector contribute between 2-3% of annual anthropogenic greenhouse gas emissions. In addition, exhaust emissions close to land influence human health negatively.

Maritime transport is subject to International Maritime Organization (IMO) regulations, which pertain to the emissions from international merchant ships through Annex VI of MARPOL 73/78, the International Convention for the Prevention of Pollution from Ships. Among others, Annex VI regulates specifically the sulphur content in marine fuels, with decreasing limits up to 2020.

While the life cycle inventory database Ecoinvent contains data on heavy fuel oil production with a sulphur content of 3.5%, there is a necessity, in light of the new regulations, to establish a better understanding of the environmental impacts and challenges associated with the production of marine fuels of different qualities.

The main objective of this work is to establish a life cycle inventory model and assess the environmental impacts of marine fuel production with different sulphur contents.

The analysis should include the following elements:

1. A literature study on the quality and types of marine fuels.
2. Development of a life cycle inventory model of several marine fuels of different quality.
3. Environmental impact assessment of marine fuels of different quality.
4. Analysis and discussion of the results in light of the IMO regulations on sulphur emissions.

The project work comprises 30 ECTS credits.

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.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

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, 15. January 2017



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Preface

To Pedro, I thank you for your unconditional support and love on this journey, and always. To my mother and closest friends that were there for me with providential support and motivation. To my best co-supervisor, Evert, thank you for your all-enduring patience and kindness over the past year. And for last but not least, thank you to my supervisor, Prof. Anders Strømman, for all insights along this journey.

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Trondheim, July 2017

Abstract

Currently, maritime transport represents over 80% of the global trade, and accounts for a significant share of the total global emissions of CO₂, NO_x and SO_x. Due to the increased awareness of the impacts of maritime transport on climate, human health and ecosystems, regulations were enforced by the International Maritime Organization (IMO) to decrease NO_x and SO_x emissions, and several abatement measures were proposed as a means to decrease CO₂ emissions.

Low-sulfur marine fuels have been pointed out as an option to comply with the tightening regulations with regards to SO_x emissions, both inside and outside maritime Emissions Control Areas (ECAs). In this context, this study aims to assess if a low-sulfur marine fuel, LSHFO, leads to a decreased impact from a life cycle perspective when compared to the most used fuel by the maritime sector, heavy fuel oil (HFO). The study comprises the modeling of a generic refinery, providing a step forward from previous research in the assessment of marine fuel impacts at the refinery gate, as well as the modeling of a Bulk Carrier operation, thus comprising a full life cycle assessment.

Results showed that at the refinery gate, crude oil extraction is the process that contributes most to the total impacts associated with the production of HFO and LSHFO. For LSHFO, it was found out that hydrogen and electricity production also play an important role, due to the sulfur removal process. On the other hand, from a life cycle perspective, results showed that the combustion of HFO and LSHFO during the operation phase is the most contributing process for the total impacts towards GWP and TAP, and also present a significant contribution for PMFP and MEP. In addition, results pointed out that a shift from HFO towards LSHFO presents trade-offs between impact categories. LSHFO presented a worst environmental performance than HFO in terms of impacts on climate, leading to an increase of approximately 2% for GWP. It was found out that this increase occurs upstream, during the refining process of LSHFO due to higher energy and hydrogen requirements, and increases are only partly offset during the operation phase. Nonetheless, results showed a 47% and 19% decrease of the total impacts towards TAP and PMFP when LSHFO is used instead of HFO, which is directly linked to the reduced sulfur content of the fuel.

Sammendrag

Maritim transport utgjør over 80% av global handel, og er ansvarlig for en betydelig andel av globale utslipp av CO₂, NO_x og SO_x. Økt oppmerksomhet rundt effekten av maritim transport på klima, menneskelig helse og økosystemer har ført til at IMO - the International Maritime Organization - har iverksatt reguleringer for å redusere utslipp av NO_x og SO_x, og flere utslippsreducerende tiltak har vært foreslått for å redusere CO₂ - utslipp.

Marine drivstoff med lavt svovelinnhold har vært pekt på som et mulig tiltak for å imøtekomme strengere regulering og regelverk for SO_x-utslipp, både innenfor og utenfor maritime utslippskontrollområder (ECAs - Emission Control Areas). Med dette som bakteppe, søker denne studien å besvare hvorvidt et lavsvovel marint drivstoff (LSHFO) gir redusert miljøpåvirkning i et livsløpsperspektiv, sammenlignet tungolje (HFO - Heavy Fuel Oil) som er det vanligste marine drivstoffet. Studien omfatter modellering av et generisk raffineri, noe som representerer et steg fremover i forhold til tidligere forskning på miljøeffekter av raffineringsteget. I tillegg er drift av tørrlasteskip modellert, og gir dermed en komplett livsløpsvurdering.

Resultatene viser at frem til drivstoffet forlater raffineriet, er de største utslippene ved produksjon av HFO og LSHFO knyttet til utvinning av råolje. For LSHFO spiller også produksjon av hydrogen og elektrisitet for prosessen med fjerning av svovel, en viktig rolle. På den annen side viser resultatene at forbrenning av HFO og LSHFO i driftsfasen utgjør det viktigste bidraget til totalutslipp for GWP og TAP, samtidig som det gir et betydelig bidrag også for PMFP og MEP. Resultatene viser videre at en overgang fra HFO til LSHFO gir ulike trade-off mellom påvirkningskategorier. LSHFO har en dårligere miljøprestasjon enn HFO når det gjelder klimagassutslipp, og gir en økning på omtrent 2% for GWP. Årsaken til dette er å finne oppstrøms i verdikjeden, i forbindelse med raffineringprosessen av LSHFO og på grunn av økt energi- og hydrogenbehov, og dette utlignes bare delvis i driftsfasen. Uansett, resultatene viser en reduksjon i totale utslipp på henholdsvis 47% og 19% for kategoriene TAP og PMFP ved overgang fra HFO til LSHFO, og denne reduksjonen er direkte knyttet til redusert svovelinnhold i drivstoffet.

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List of Abbreviations

AP	Acidification potential
ALOP	Agricultural land occupation potential
BTL	Biomass-to-liquid biofuel
CO ₂	Carbon dioxide
EEDI	Efficiency design index
ELCD	European life cycle database
EOL	End-of-life
EP	Eutrophication potential
ECA	Emission control area
FCC	Fluid catalytic cracker
FDP	Fossil depletion potential
FEP	Freshwater eutrophication potential
FETP	Freshwater ecotoxicity potential
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential
HDS	Hydrodesulfurization process
HFO	Heavy fuel oil
HTP	Human toxicity potential
IMO	International maritime organization
IPCC	International panel on climate change
IRP	Ionizing radiation potential
kg	Kilogram
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LBG	Liquefied biogas
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LSHFO	Low-sulfur heavy fuel oil
LTP	Land transformation potential

MDO	Marine diesel oil
MEP	Marine eutrophication potential
METP	Marine ecotoxicity potential
MGO	Marine gas oil
MRDP	Metal resource depletion potential
NO _x	Nitrogen oxides
ODP	Ozone depletion potential
PMFP	Particulate matter formation potential
POFP	Photochemical oxidant formation potential
RME	Rapeseed methyl ester
SCR	Selective catalytic reduction
SEEMP	Ship Energy Efficiency Plan
SO ₂	Sulfur dioxide
SO _x	Sulfur oxides
TAP	Terrestrial acidification potential
TETP	Terrestrial ecotoxicity potential
tkm	ton kilometer
TTP	Tank-to-propeller
ULOP	Urban land occupation potential
WDP	Water depletion potential
WTP	Well-to-propeller
WTT	Well-to-tank

1 Introduction

Maritime transport represents over 80% of the global trade and it is responsible for 3.1% of the total anthropogenic carbon dioxide (CO₂) emissions, which are expected to increase between 50% and 250% by 2050, if no measures are implemented (Asariotis et al. 2016; Smith et al. 2015). This is in complete disagreement with the target proposed by International Panel on Climate Change (IPCC), which aims to decrease global CO₂ emissions by 2050 to at least 50% of 1990 levels (European Commission 2017).

Taking these figures into account, regulations aiming at a decrease in CO₂ emissions have been developed. However, focus has now been placed on regulating emissions of nitrogen oxides (NO_x) and sulfur oxides (SO_x), to which maritime transport contributes to a significant share (Buhaug et al. 2009; Smith et al. 2015).

In order to comply with the new and tightened regulations on NO_x and SO_x emissions, several measures have been proposed. From the long list of proposed measures, the increase of energy efficiency in the power and propulsion systems, and the use of low-carbon fuels, among others, are included (Buhaug et al. 2009). Additionally, the use of exhaust gas scrubbers and selective catalytic reduction (SCR) technologies were also suggested as a means to decrease SO_x and NO_x emissions during the operation phase (IMO 2015). However, the number of studies assessing the proposed measures over a life cycle perspective is very limited. Moreover, most of the studies assess the environmental performance of marine fuels by considering a sulfur content that is not in conformity with the most recent regulations on SO_x emissions.

In light of new regulations, it is of high importance to assess and better understand the environmental impacts of low-sulfur marine fuels from a life cycle perspective. For this reason, in this study, a life cycle inventory of a generic refinery will be developed to account for and allocate environmental impacts related with the production of (low-sulfur) marine fuels as well other crude oil-based fuels.

1.1 Goal of the study

The goal of the study is to assess and compare the environmental impacts of a marine fuel with different sulfur contents, over a life cycle perspective, aiming to understand whether a low-sulfur marine fuel is a promising solution to decrease emissions from the maritime sector.

The fuel considered is heavy fuel oil (HFO) with a sulfur content of 3.5% and 0.1%. The latter is most commonly referred to as low-sulfur heavy fuel oil (LSHFO). The choice has to do with the fact that HFO is the most used type of fuel within the maritime sector, both because of its energy efficiency and market price (Chryssakis et al. 2014). A sulfur content of 3.5% is considered to allow for comparison with previous research within this topic, whereas the selection of a sulfur content of 0.1% is due to the tightened regulations on SO_x emissions, described in Section 2.2. In addition, the selection of different sulfur contents allows a comparison of the overall impacts and a further analysis with regards to the trade-offs that might occur due to a shift towards LSHFO.

In order to assess environmental impacts related to marine fuel production, a life cycle inventory (LCI) model of a generic crude oil refinery, including inflows, outflows, emissions, and energy usage of the main refining processes is developed. This is expected to allow for an improved assessment of the impacts associated with the HFO and LSHFO production at the refinery gate. Thereafter, the aim is to assess the environmental impacts due to the combustion of the HFO and LSHFO in a Bulk Carrier.

The following research questions will be discussed during this study:

- What are the key findings from previous research on the life-cycle impacts of marine fuels?
- What are the major life cycle environmental impacts generated by HFO and LSHFO at the refinery? And what are the main contributors to the total impacts?
- Are there differences in results between the different allocation methods considered?
- Considering a life cycle perspective, what is the contribution of the different life cycle phases? Which is the most relevant one?
- Is LSHFO a promising solution to decrease emissions of maritime sector? Are there trade-offs?

1.2 Scope of the study

To assess the environmental impacts associated with the production and usage of HFO and LSHFO, a life cycle approach methodology is applied. The model covers the life cycle impacts resulting from the extraction of crude oil and its processing at the refinery site, to the transportation of HFO and LSHFO from the refinery to a Bulk Carrier and its further usage during the vessel's operation. Vessel's construction and end-of-life (EOL) are also included. Therefore, a full LCA is carried out in this study. The LCA methodology applied is in line with the ISO 14044 and 14044 standards (ISO 2006b, 2006a), as described in Chapter 3.

Regarding the functional unit, two types were defined, one for the refining phase and another for the vessel's operation phase. At the refining phase, a functional unit per kilogram (kg) of output was defined, while at the operation, one tonne of cargo transported over one kilometer (tkm) was considered. The selection of these functional units has to do with the fact that it enables the comparison of the results from previous and future studies within the topic. In what concerns to results, they will be presented for the environmental impact categories included in the ReCiPe method, following the ReCiPe hierarchist impact assessment model (Goedkoop et al. 2013).

The assessed life cycle of both HFO and LSHFO is depicted in the process flow diagram presented Figure 1, where unit processes are represented as boxes, and flows as arrows. The system is divided into background and foreground processes. Background processes are modeled based on a generic database, while foreground processes are modeled with specific data for this study. Furthermore, the flow diagram presents the two systems that comprises the total system boundaries of this study: the refining and vessel's operation systems. The former is marked with a blue background and a blue dotted line, with a functional unit of 1 kg fuel, whereas the latter is marked with a grey background and dotted line, with an associated functional unit of 1 tkm.

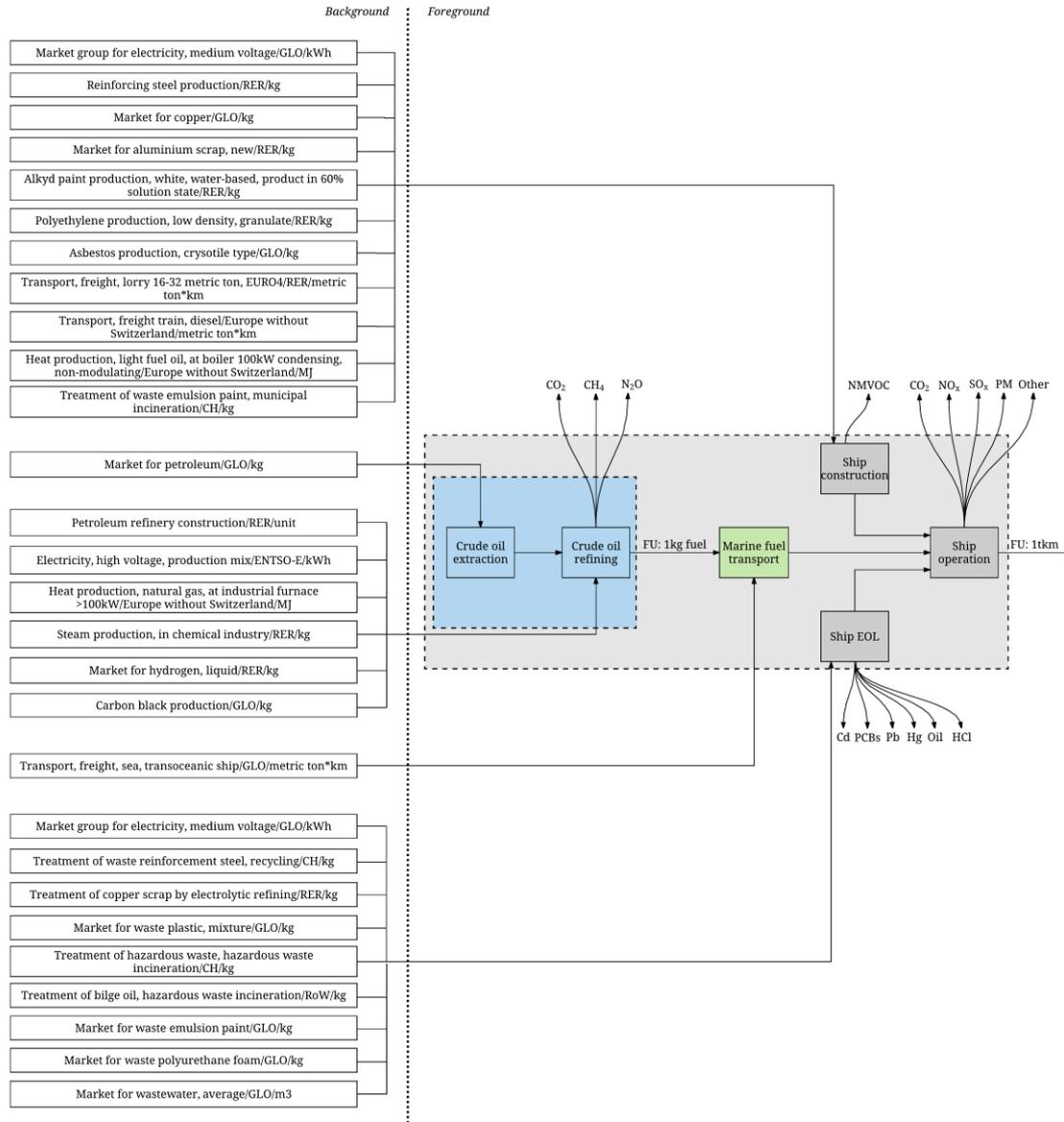


Figure 1: Flow diagram of the studied system

1.3 Thesis outline

The thesis is divided in 7 chapters and includes one appendix, hereafter referred to as Digital Appendix A, which comprises all supporting information.

Chapter 2 presents the relevant background for this study. The chapter is divided into three main sections. In the first section, the most relevant pollutants from maritime transport and its associated impacts on climate, human health and ecosystems will be

presented. In addition, current and near-future regulations on air pollution associated with maritime transport will be summarized and abatement options proposed to decrease CO₂ emissions will be described. A description of the refining processes of a generic refinery as well as the desulfurization process required to produce LSFHO will be then presented in the second main section of this chapter. Lastly, in the third main section, key findings from previous research on the life cycle impacts of marine fuels will be presented.

Chapter 3 describes the methodology applied in this study. A theoretical overview of the LCA framework will be presented as well as the methodology used to deal with the allocation issue at the refinery. In addition, the tools used in this study to apply the methodology will be presented.

In Chapter 4, the life cycle inventory chapter, the system analyzed will be defined and described in detail. The methodological choices of this study will be explained together with the data collection and modeling process.

Thereafter in Chapter 5, the study results will be presented per functional unit for the environmental impact categories included in the ReCiPe method, following the ReCiPe hierarchist impact assessment model. Please note that this chapter will only present the impacts at the refinery gate, i.e. per kg fuel. The impacts per tkm will be presented in the following chapter.

In Chapter 6 results will be further interpreted and discussed. The chapter is divided into four main sections. Firstly, the impacts over a life cycle perspective will be presented, and thereafter a comparison between this study results and previous research within the topic of marine fuels LCA will be performed. In the third main section of this chapter a sensitivity analysis will be performed for variables that were considered relevant in terms of associated uncertainty. Issues such as data uncertainty and limitations of the study will be addressed. Lastly, suggestions for further research will be discussed.

Chapter 7 provides a conclusion based on the outcome of the analysis and on the research questions considered.

2 Background

This chapter presents the relevant scientific background for this study. Section 2.1 presents the different emissions associated with maritime transport and briefly describes its impact on climate, environment and human health. In Section 2.2, the current and near-future regulations on air pollution associated with maritime transport are presented, and in Section 2.3 abatement options and their potential are summarized. Thereafter the production process of HFO and LSHFO is presented in Section 2.4, including a brief description of the processes that comprises a general refinery scheme. Finally, on Section 2.5, a literature review of studies assessing the environmental impacts of marine fuels is presented, including key findings and studies limitations.

2.1 Emissions from maritime transport

Maritime transport is the backbone of globalization as it is the main means of cross-border transportation. According to Buhaug et al. (2009), maritime transport presents a much higher efficiency in terms of CO₂ emissions when compared with rail and road transport modes. However, the pollution awareness associated with this transportation mode has been increasing over the last decades, with a significant number of studies addressing it as a significant source of pollution (Buhaug et al. 2009; Cofala et al. 2007; Corbett and Winebrake 2008; Eyring et al. 2010; Smith et al. 2015)

CO₂ emissions from maritime transport account for 1,015 million tons per year, which corresponds to 3.1% of the total global anthropogenic emissions (Smith et al. 2015). This makes CO₂ emissions one of the most important pollutants associated with maritime transport, both in terms of quantity emitted and of global warming potential (GWP), due to its residence time in the atmosphere. CO₂ emissions occur during the combustion process and are highly dependent on the carbon content of the fuel as well as on the amount of marine fuel combusted. Therefore, effective measures to reduce its emissions might comprise a shift towards low-carbon fuels or an increase in the efficiency of power and propulsion systems, as further explained in Section 2.3. In addition to CO₂, maritime transport is also responsible for a significant share of other gases, such as NO_x and SO_x,

which account for 15% and 13% of the total global anthropogenic emissions, respectively (Smith et al. 2015).

The emission of NO_x results from an endothermic reaction between nitrogen and oxygen during the combustion process, at high temperatures. The high share of NO_x emissions from shipping is due to the fact that most marine engines operate with high temperatures and pressures, associated with the lack of implementation of effective reduction technologies (Eyring et al. 2010). NO_x is one of the main precursors of ozone formation, which can lead to adverse effects on human health such as damage to lung tissue and reduction in lung function, especially in susceptible populations (EMSA 2016b). Additionally, NO_x emission also contributes to smog and acid rain formation, as well as to acidification and eutrophication. The impacts of eutrophication are associated with a violent algae growth and consequent decrease of oxygen levels in freshwater bodies, as well as to an increased level of toxins that are harmful to fish or other aquatic life. The acidification, on the other hand, occurs due to the increased concentration of nitrogen in the soils, which leads to a decrease of pH and subsequent disturbing of ecosystems natural balance.

Regarding SO_x emissions, they also occur during the combustion process, but on the contrary of NO_x, SO_x emissions are directly linked to the sulfur content of the combusted marine fuel (Eyring et al. 2010). This means that it requires effective reduction technologies upstream from the fuel combustion, i.e. at the refining process. The impact of sulfur emissions is expressed through acidification, which impacts on ecosystems were already described, and acid rain, which causes damage to buildings and can lead to the death of aquatic ecosystems or other wildlife. Besides, SO_x emissions can affect heart and lung functions on humans (EPA 2017a). Therefore, sulfur emissions are a main concern, especially in coastal areas where maritime transport is expected to be responsible for 50% of sulfur deposition in coastal areas in Europe in 2020 (Cofala et al. 2007).

As maritime transport emissions impose a risk to both human health and ecosystems, at a local level, due to NO_x and SO_x emissions, and at a global level, mostly due to CO₂ emissions, pressure has been made on the authorities to enact regulations to the maritime sector. Most of them have been taken through Annex VI of MARPOL, an international instrument developed by the International Maritime Organization (IMO) that establishes

international standards to regulate specific emissions generated by maritime transport. The following section presents a review of the current regulations applied to the marine sector.

2.2 Emission regulations

Emissions from maritime transport are regulated both by national laws, in which the ship is registered, and by international laws and regulations. In addition, ships must comply with regulations of ports and waters in which they operate.

The international laws and regulations associated with maritime transport are regulated by IMO, the United Nation agency responsible for the safety and security of shipping and for preventing the pollution by ships. In 1973, IMO adopted the International Convention for the Prevention of Pollution from Ships, known as MARPOL, which applies to 99% of the world's merchant tonnage (IMO 2017f). The Annex VI of MARPOL 73/78 - *Regulations for the prevention of Air Pollution from ships*, entered into force in May 2005 with the aim to reduce the air pollution impact from shipping. The Annex sets limits on SO_x and NO_x emissions from ship exhausts and outlaws deliberate emissions of ozone depleting substances among other regulations (IMO 2017e). Limits for the emission of SO_x and NO_x are set by geographical location, and thus they differ whether the emission occurs within or outside the emission control areas (ECAs).

The currently existent ECAs are the following, Baltic sea, North Sea, North America, and United States and Caribbean Sea areas. However, while SO_x limits are applied in all stated areas, NO_x limits are only applied in North America, and United States and Caribbean Sea areas (IMO 2017d). The introduction of ECAs is an attempt to decrease emissions in areas where due to their oceanographical and ecological conditions and sea traffic, the adoption of special mandatory measures is required (IMO 2017d).

Regarding the limits of sulfur emissions, Annex VI sets a mandatory global cap for all ships in accordance with the location where the emission occurs, i.e. if it is emitted inside or outside ECA. According to the new regulation, the sulfur cap must be reduced from 3.50% to 0.50% by 1 January 2020 outside ECA, and inside ECA a sulfur cap of 0.10%

entered into force since 1 January 2015, as presented in Table 1 (Smith et al. 2015). In this sense, ships that operate both inside and outside ECAs will need to switch to lower sulfur marine fuels to comply with the different limits. Notwithstanding, it is noteworthy that the new sulfur limits outside ECA are subject to a feasibility review that is expected to be completed no later than 2018, but that can be deferred to 1 January 2025 (IMO 2017c).

As an extension to Annex VI, European Union has set a limit of sulfur content in marine fuels for harbor regions to 0.10% in 2010, by implementing the Directive 2005/33/EC (EMSA 2016a).

Table 1: Sulfur limits defined after IMO

Outside ECA	Inside ECA
4.50% m/m prior to 1 January 2012	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 2010
0.50% m/m on and after 1 January 2020	0.10% m/m on and after 1 January 2015

NO_x emission limits, on the other hand, are regulated based on the ship construction date, and apply for diesel engines of over 130 kilowatts (kW) output power. They are divided into Tier I, II and III. Tiers I and II apply globally, whereas Tier III only applies to North America Sea, and United States and Caribbean Sea ECAs. Furthermore, Tier II and III set NO_x emission limits for new engines, and Tier I for existing pre-2000 engines. (IMO 2017b).

NO_x limits are related with engine's rated speed, n , measured in revolutions per minute (rpm). Table 2, presents NO_x emission limits for $130 < n \leq 2,000$ (Smith et al. 2015).

Table 2: NO_x limits defined after IMO

Tier	Ship construction date	NO _x limit [g/kWh]
I	1 January 2000	$45 * n^{-0.2}$
II	1 January 2011	$44 * n^{-0.23}$
III	1 January 2016	$9 * n^{-0.2}$

Despite the development of regulations to limit SO_x and NO_x emissions, international shipping is still excluded from global emission targets such as the Kyoto protocol or the Paris agreement, and thus greenhouse gas (GHG) emissions are still not directly targeted. Nonetheless, it is noteworthy that IMO has developed regulations towards the decrease of CO₂ emissions, with significant efforts being directed on finding the best technological and operational way to mitigate CO₂ emissions.

In 2013, technical measures for new ships and operational measures for all ships entered into force, setting a global mandatory decrease of GHG emissions for the first time. The adopted measures were added to MARPOL Annex VI – *Regulations on energy efficiency for ships*, and apply to all ships over 400 gross tonnage and above. It comprises the Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Plan (SEEMP) for all ships.

The EEDI is expressed in grams of CO₂ per ship's capacity-mile, which means that the smaller the EEDI is, the more energy efficient is the ship design (IMO 2017a). Its aim is to promote an improved design efficiency, by establishing minimum energy efficiency requirements for new ships. However, this technical measure has some limitations since it only applies to new ships and does not consider operational measures. The SEEMP, on the other hand, is a management plan that aims to improve ship's energy efficiency by identifying options to reduce emissions in a cost-effective manner (IMO 2017a).

With the aim to further regulate the GHG emissions from international shipping, Market-Based measures were proposed in addition to technical and operational measures (IMO 2017a). The proposed measures range from contribution schemes for CO₂ emissions, via emission trading systems, such as the Global Emission Trading System, to schemes based on ship's efficiency, e.g., Vessel Efficiency System (IMO 2017a). An overview of the technical and operational abatement options to decrease GHG emissions from maritime transport is presented in Section 2.3.

2.3 Abatement options

As shown in Section 2.1, maritime transport is a significant source of air pollution with significant impacts on climate, health and environment. Regulation has been enacted for SO_x and NO_x emissions, and CO₂ emissions, the most important GHG, are starting to be regulated, as shown in Section 2.2. Therefore, in this Section, the existent abatement options to decrease emissions from maritime transport are presented.

According to Buhaug et al. (2009), the abatement options for reducing emissions from shipping can be divided into the following four fundamental categories:

1. Improving energy efficiency, i.e. doing more useful work with the same energy consumption, applied to both the design and the operation of ships.
2. Using renewable energy sources, such as the wind and solar power.
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.

Each fundamental category comprises a significant number of operational and technological measures that were evaluated in terms of their potential to decrease CO₂ emissions. Table 3 presents the estimated percentage of CO₂ savings per tonne-mile for the considered measures (Buhaug et al. 2009).

Table 3: Potential CO₂ savings from technological and operational measures

	Savings [CO ₂ /ton-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%

Table 3 (cont.): Potential CO₂ savings from technological and operational measures

	Savings [CO ₂ /ton-mile]
Operation (All ships)	
Fleet management, logistics and incentives	5% to 50%
Voyage optimization	1% to 10%
Energy management	1% to 10%

Some of the findings presented in Table 3 are in line with previous research. In what concerns operational measures, a study published in 2011 found that CO₂ emissions can be reduced by 33% from a baseline scenario in 2030 at a marginal abatement cost of USD 0 per ton (Eide et al. 2011). This suggests that significant profitable measures for fuel and emission reductions can be achieved. Another study concludes that lower speed leads to lower fuel consumption, which consequently leads to a decrease in emissions (Lindstad et al. 2013). Buhaug et al. (2009), also stated that increased efficiency of cargo handling, berthing and mooring at ports could represent a potential reduction in ship emissions.

Regarding ship design, a study has proposed as a profitable abatement option the replacement of the existing fleet by larger vessels (Lindstad et al. 2012). According to the study results, this measure can lead to savings in emissions up to 30% at a negative abatement cost per ton of CO₂. Other studies assessed the environmental impacts of substituting the conventional marine fuels with biofuels, thus assessing the possible savings associated with low-carbon fuels (Bengtsson et al. 2012; Chryssakis and Stahl 2013; Øberg 2013). Bengtsson et al. (2012) concluded that biofuels could be a possible measure to decrease the global warming impact from shipping, but to the expense of greater environmental impact for some other impact categories, such as eutrophication potential. Still regarding ship design, a study published in 2015 indicates that hybrid solutions are cost-competitive with traditional engine setups, and that can also lead to a reduced fuel consumption and hence, to reduced emissions (Lindstad et al. 2015).

This study assesses the environmental impacts from using a low-sulfur marine fuel when compared to one with a sulfur content of 3.5%, hence comprised in the third fundamental category. HFO is the marine fuel assessed and thus a brief description of its refining process is presented in Section 2.4. Thereafter, in Section 2.5, key findings and limitations

from previous environmental assessments related to the objective of this study and to the third option category are presented.

2.4 HFO production

After being extracted from the ground, crude oil is transported to the refinery site to be further converted into commercial petroleum products. In average, a barrel of crude oil results into 43.3% gasoline, 22.4% diesel, 8.7% jet fuel and 3.8% of HFO, comprising approximately 80% of the refinery products (Jones and Mayfield 2016). From these, the global merchant fleet consumes up to 85% of HFO with a high sulfur content, the remaining 25% being distillate fuels with lower sulfur contents (Chryssakis et al. 2014). This is mainly associated with the lower price of HFO since it is pure or nearly pure residual oil, thus making it attractive to maritime sector, which requires larger quantities of fuel.

However, in order to comply with the current and near future regulations on SO_x previously described in Section 2.2, the demand for low sulfur marine fuels is expected to increase in the next five to ten years (Chryssakis et al. 2014; Argyros et al. 2014). This in turn, is expected to lead to increased prices of distillate fuels, such as marine diesel oil (MDO), marine gas oil (MGO) and LSHFO, since the refinery capacity might be insufficient to meet the increasing demand of such products.

In the next section, the main refinery processes to produce HFO are briefly described.

2.4.1 Refining process

At the refinery site, the crude oil is converted into commercial petroleum products through a significant number of processes. The combination of the processes used at a refinery may vary depending on refinery location, consumer demand and market prices. The configuration of a generic refinery as well as the main inputs and outputs of each process is presented in Figure 2, followed by a brief description of the processes considered (Abella et al. 2016b).

into fuels that can be used by the transportation sector, such as HFO (Pellegrino et al. 2007).

The fractions of naphtha, kerosene and diesel that result from the atmospheric distillation process, are thereafter hydrotreated. The aim of the hydrotreating process is to reduce the sulfur and nitrogen contents, as well as to saturate olefins or aromatic rings presented in these fractions. This is done without changing the boiling range of the fraction to meet specifications of feedstock for further processing, or specifications of end products. Regarding the sulfur removal, it is done by reacting hydrogen with sulfuric compounds in order to form new compounds that can easily be separated. After being hydrotreated, diesel fraction results into a usable fuel – diesel or ultra-low sulfur diesel (ULSD), while naphtha and kerosene fractions require further processing. Kerosene fraction follows to the merox unit where a catalytic chemical process removes mercaptans from the kerosene stream, resulting in a usable fuel – jet fuel. Naphtha, on the other hand, follows two different pathways to be further converted into gasoline. The light straight run (LSR) of naphtha fraction is further processed by isomeration, while the heavier is processed through catalytic reforming. The isomeration process aims to increase the gasoline octane by modifying the structure of hydrocarbons through a series of isomerization and cyclization reactions, where in the presence of a catalyst the paraffines are rearranged into isoparaffines. Catalytic reforming is used to produce gasoline from the less desirable naphtha fraction. It further processes the stream from the hydrotreated naphtha by breaking it into lighter fractions by using a catalyst. This results in a product with significantly higher octane rating than the initial naphtha, and that can be added to the gasoline pool. One of the byproducts of this unit is the associated hydrogen production, that can be further used in other processes in the refinery. (Abella et al. 2016b)

Regarding the heavier fractions, two fractions result from the atmospheric distillation - the atmospheric residue (AR) and the atmospheric gas oil (AGO) fractions. The AR is sent to the vacuum furnace which has the same function as atmospheric furnace, and thereafter sent to vacuum distillation, to further gas oil recovery or to fuel oil production. The vacuum distillation works in the same way as the atmospheric distillation, differing in the fact that it operates at low pressures and higher temperatures to further crack the molecules present in the stream. The vacuum distillation results in three streams, light vacuum gas oil (LVGO), heavy vacuum gas oil (HVGO) and vacuum residue (VR),

which are further sent to gas oil hydrocracking unit or directly to the fluid catalytic cracker (FCC) unit, except the latter that is added to the HFO pool. The atmospheric gas oil (AGO) is further sent as well to gas oil hydrocracking unit or directly to the fluid catalytic cracker (FCC) unit to be further processed. (Abella et al. 2016b)

The gas oil hydrocracker and fractionator units aims to further break and separate the heavy hydrocarbon molecules presented in the heavier fractions into smaller hydrocarbon molecules, to increase the yield of premium fuels like diesel and gasoline. This is done by using a catalytic agent to accelerate the cracking process. FCC is the most widely used catalytic cracking process in a refinery (Pellegrino et al. 2007). It also aims to further break the heavier and more complex hydrocarbon molecules into lighter molecules by using heat and a catalytic agent. The lighter molecules are then sent to a fractionator which separates them according to their properties, thus increasing gasoline and diesel yields, but mostly, gasoline yield. In addition to gasoline and diesel streams, from the FCC fractionator results slurry oil, that is also added to the HFO pool and C4 gasoline that is further processed through alkylation before being added to the gasoline pool. (Abella et al. 2016b)

Alkylation processes molecules such as isobutene and other low-molecular-weight alkenes coming from the FCC main fractionator in order to produce gasoline. This is done by adding an alkyl, such as propyl or butyl to the molecules. This process requires a strong acid catalyst and heating to produce an alkylate with a high-quality gasoline component. (Abella et al. 2016b; Pellegrino et al. 2007)

2.4.2 HFO desulfurization process

The desulfurization process, is essentially an hydrotreating process aiming to remove sulfur from petroleum fractions. Sulfur removal occurs by reacting it with hydrogen in a reactor at relatively high temperatures and at moderate pressures, resulting in its conversion to hydrogen sulfide (H₂S) (Kokayeff et al. 2015). This conversion is usually referred to desulfurization or hydrodesulfurization (HDS) process.

The operational conditions of an HDS process are highly dependent on feed type, degree of desulfurization, metal levels, carbon residue, and required cycle length. On the other hand, the relative ease of sulfur removal from a petroleum fraction is greatly dependent on the sulfur type present. The main sulfur types present in a petroleum fraction are mercaptans, sulfides, disulfides, thiophenes, benzothiophenes, and dibenzothiophenes. In naphtha fractions, sulfur is mainly present as mercaptans and sulfides, making relatively easier the sulfur removal (Kokayeff et al. 2015). However, in heavier fractions more difficult sulfur species are found, hence requiring more hydrogen and more hydrotreating catalyst than lighter fractions to achieve the tight ultra-low-sulfur fuel specifications driven by environmental regulations.

Regarding the hydrotreating catalysts, they are generally high-surface-area materials that uses gamma alumina, γ - Al_2O_3 , as a catalyst support. From all catalysts types, Cobalt-Molybdenum (CoMo) is the most used in HDS since it presents the highest sulfur removal per unit of hydrogen consumed (Pellegrino et al. 2007). Figure 3 depicts a simplified HDS process of a residual oil, such as HFO, while Table 4 presents the typical HDS process conditions (Kokayeff et al. 2015).

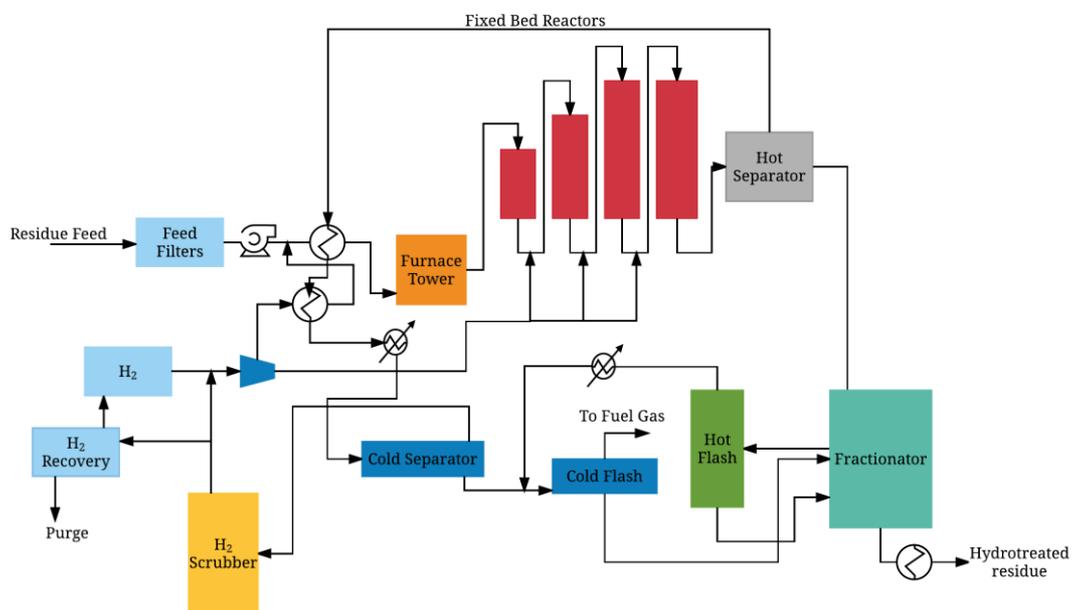


Figure 3: Flow diagram of an HDS process, from Kokayeff et al. (2015)

Table 4: Typical operational conditions of a residual oil HDS process

Variable	Amount
Temperature, °C	355 - 390
Pressure, psig	1,800 - 2,500
H ₂ /oil, Nm ³ /m ³	500 - 850

LSHFO, with a 0.1% sulfur content can be produced by HDS, however, its availability and price can be considered a constraint (Bengtsson et al. 2011).

2.5 Previous LCA studies of maritime transport

Over the last years, a significant number of studies assessing the environmental impacts of maritime transport previously described in Section 2.1, have been performed. The studies vary in goal and scope, but the large majority of them are tank-to-propeller studies, thus only focused on assessing the impacts from the combustion of marine fuels. Only a few performed an impact assessment of marine fuels over a life cycle perspective, the so-called well-to-propeller (WTP) studies. In the next section, key findings from previous research within the topic of this study are presented, followed by a brief presentation of the main methodological differences between the studies considered as well as their limitations, in Section 2.5.2.

2.5.1 Key findings from previous studies

As referred, the maritime sector is striving to find measures to comply with the stricter regulations, both inside and outside ECA, and one of the options is to shift towards a marine fuel with less fuel-cycle emissions per unit of work done. In this sense, in the last couple of years, scientists have been assessing the environmental performance of several types of marine fuels, comparing them against each other, in order to find out the best option. Within the most common types of assessed fuels are HFO, MGO and MDO. This can be explained by the fact that MGO and MDO are being used as substitutes for HFO since the tightened regulations came into force inside ECA. Other common types of

assessed fuels are liquefied natural gas (LNG) and biofuels, which performance against HFO will be briefly presented. No study assessing the impacts of LSHFO was found.

A study published in 2008 assessed the impacts of replacing residual oil with cleaner, low-sulfur fuels, such as MGO and MDO over a fuel-cycle perspective (Corbett and Winebrake 2008). The results showed that the use of MGO and MDO increases the CO₂ emissions from 0.16 to 0.47%, when compared with the use of residual oil. This is in line with the findings from Chryssakis and Stahl (2013) and Øberg (2013), who evaluate the environmental performance of marine fuels from a life cycle perspective. The former observed an increase of 0.2% towards GWP when HFO is substituted with MGO/MDO, while the later stated an increase of 1%. Both studies concluded that this increase occurs upstream, i.e. at the refining phase mostly due to increased energy requirements, being partly offset during the operation phase. Øberg (2013) also stated a decrease of approximately 76% towards acidification potential (AP), meaning a significant reduction in terms of SO_x. This is also in line with results obtained by Corbett and Winebrake (2008) who observed a decrease between 70% and 85% for SO_x emissions when comparing MGO and MDO with residual oil.

Other studies that also compared the performance of HFO against MDO and MGO, presented significant differences in results both in terms of GWP and AP, which might be explained by methodological choices, such as functional unit and system boundaries. In 2011, for example, a study compared MGO and HFO over a life cycle perspective and concluded that the former presents a decrease of approximately 2% with regards GWP, when compared to the later (Bengtsson et al. 2011). A decrease of 29% towards AP was also observed. Another study achieved similar figures, obtaining a decrease of 5% for GWP and 24% towards acidification for MGO when compared against HFO, from a life cycle perspective (Bengtsson et al. 2012). Noteworthy that both studies also assessed the eutrophication potential (EP) and no relevant decrease was obtained when comparing HFO with MGO, meaning that NO_x emissions are essentially the same for both type of fuels. On the other hand, Øberg (2013) stated a decrease of 2% towards EP by comparing MGO/MDO against HFO. Verbeek et al. (2011), also assessed the environmental performance of HFO and MGO/MDO, among other type of fuels and concluded that by substituting HFO with MGO/MDO a decrease 0.5% towards GWP can be achieved. This

result is four and ten times lower than the result obtained by Bengtsson et al. (2011) and by Bengtsson et al. (2012), respectively.

Regarding LNG and biofuels performance over a life cycle perspective, a significant number of studies agree that both are a possible option to decrease the global warming impact from shipping. However, some studies also concluded that biofuels can lead to increased impacts towards acidification and eutrophication.

Bengtsson et al. (2011) observed a decrease towards AP and EP of approximately 90% by using LNG from North Sea instead of HFO. However, the use of LNG does not decrease the GWP by more than 12%, which is mainly associated with the magnitude of the methane slip from the gas engine. Verbeek et al. (2011), also concluded that among the fuels analysed, LNG was the fuel alternative that presents lower impacts towards GWP. Chryssakis and Stahl (2013), also concluded that LNG is a promising alternative, considering its contribution towards GWP, as well as its price and availability. Bengtsson et al. (2012) assessed the environmental impacts of substituting HFO with LNG and its further substitution by biofuels until 2025. When compared with HFO, LNG presented a decrease in impacts of approximately 14%, 72% and 25% towards GWP, AP and EP, respectively. Furthermore, all biofuels considered in this study presented a much better performance towards GWP than HFO and LNG. However, the results showed that some biofuels present a significantly higher acidifying potential than LNG, and a much higher eutrophication potential than LNG and HFO, as the case of rapeseed methyl ester (RME) and biogas-to-liquid biofuel (BTL). This is in line with the results found by Øberg (2013), with the biofuels presenting, in average, a decrease potential of approximately 70% and 54% towards GWP and AP, respectively, and a significantly higher increase towards EP, 250%, in average, when compared to HFO. Brynolf et al. (2014), compared the life cycle environmental performance of LNG, liquefied biogas (LBG), methanol and bio-methanol as alternative marine fuel choices to the conventional HFO and concluded that a shift from HFO towards LNG or methanol produced from natural gas would lead to an overall improvement of the environmental performance of maritime transport.

2.5.2 Methodological differences

In this section, the methodological choices of the studies considered in Section 2.5.1 are briefly analyzed. Emphasis will be put on the refining phase, aiming to understand the type of data used, the type of allocation performed and the sulfur content of the fuels assessed, especially with regards HFO.

Regarding the scope of the studies, they differ in terms of system boundaries, functional unit and impact categories assessed. With respect to system boundaries, none of the studies considered the manufacturing and EOL of capital goods, e.g. the construction and EOL of vessel. However, most of the studies stated that were performing an environmental assessment of marine fuels from a life cycle perspective (Bengtsson et al. 2011; Bengtsson et al. 2012; Brynolf et al. 2014; Chryssakis et al. 2014; Øberg 2013; Verbeek et al. 2011).

Another important aspect with regards to the scope of the study, is the definition of functional unit, which varies from study to study, not allowing a direct comparison of results. For example, Bengtsson et al. (2011) and Brynolf et al. (2014) presented the results per tkm, while Øberg (2013) and Bengtsson et al. (2012) defined as functional unit one year of operation. On the other hand, Chryssakis and Stahl (2013) and Verbeek et al. (2011) presented the results per MJ of fuel combusted. Another important aspect that also has influence on the total results is the vessel considered during the combustion phase. Most of studies considered a RoPax vessel, but Øberg (2013), for example, also considered a container vessel in the analysis. Lastly, some studies performed an analysis based on a single impact category, such as GWP (Chryssakis et al. 2014; Verbeek et al. 2011). This presents a drawback since trade-offs that might occur are not analyzed neither discussed.

Regarding the refining phase, none of the studies developed a life cycle inventory for the production of HFO, but used instead databases such as *European Life Cycle Database (ELCD)* and *Ecoinvent*. In both databases, the impacts of HFO production are allocated after each sub process in the refinery based on lower heating value of the streams, i.e. on their energy content. Nonetheless, it should be taken into account that *ELCD* considers

the production of HFO with a sulfur content of 1.0%, while *Ecoinvent* considers a sulfur content of 3.5%.

The key findings and main methodological differences from the considered studies are summarized in Table 5.

Table 5: Key findings and methodological differences from previous studies

Study	System Boundaries	Indicator/ Pollutant	Fuel type	FU	Key findings
Cobertt and Winebrake (2008)	Fuel-cycle	CO ₂ , SO ₂	Residual oil, MGO and MDO	trip	CO ₂ emissions increase between 0.16-0.47% due to a shift from HFO to MGO/MDO; SO _x emissions decrease between 70%-85%.
Bengtsson et al. (2011)	WTP	GWP, AP and EP	HFO, MGO, GTL and LNG	tkm	GWP decreases approx. 2% from a shift towards MGO; AP decreases 29%; For EP, no relevant decrease was obtained.
Verbeek et al. (2011)	WTP	GWP	HFO, LNG, MGO/MDO and EN590	MJ	GWP decreases 0.5% due to a shift from HFO to MGO/MDO.
Bengtsson et al. (2012)	WTP	GWP, AP, EP and others	HFO, MGO, RME, BTL, LNG and LB-CH ₄	year of operation	GWP decreases 5% and AP 24% when comparing MGO against HFO; For EP, no relevant decrease was obtained.
Øberg (2013)	WTP	GWP, AP, EP and others	HFO, MDO/MGO, LNG, Methanol, DME, FT-Diesel	year of operation	GWP increases 1%; AP decreases approx. 76%; and EP decreases 2% towards EP by comparing MGO/MDO against HFO.
Chryssakis and Stahl (2013)	WTP	GWP	HFO, MGO/MDO, low sulfur diesel, LNG, CNG, LPG, Methanol, Ethanol, Biodiesel, liquefied biogas	MJ	GWP increases 0.2% when HFO is substituted with MGO/MDO.

3 Methodology

In this Chapter, the advantages associated with the use of life cycle assessment as an environmental impact assessment tool will be presented. From Section 3.1.1 to Section 3.1.4 a brief description of the LCA framework is given. Lastly, Section 3.2 describes the tools used in this study. The methodological choices for this thesis will be explained in the following Chapter, together with the data collection and modeling process.

3.1 Life Cycle Assessment

Life cycle assessment is a tool that enables the evaluation of a product environmental performance throughout its whole life cycle, i.e. from raw materials extraction, through production, usage, end-of-life treatment and final disposal (ISO 2006b). In this sense, as it presents a holistic overview of a product system, it allows to identify the most relevant environmental impacts as well as the contribution of the different life cycle phases to the total impacts. Besides, it helps to avoid potential shifting of environmental impacts between the different phases of a product's life cycle, or from one environmental impact to another (ISO 2006a).

LCA can be employed to serve different applications, such as to compare different products or services that fulfill the same function, identify improvement opportunities in a production system, and as support for decision making (Baumann and Tillman 2004).

Figure 4 illustrates the life cycle of a marine fuel. It shows the process chain from crude oil extraction through transportation and refining until use in the ship, comprising a WTP analysis as well as a well-to-tank (WTT) and tank-to-propeller (TTP) analysis. Note that the refining process is a multi-output process, i.e. other fuels than marine fuels are produced by the refinery. This is indicated by the question mark. As a result, impacts need to be allocated among the different refinery products, as further explained in Section 3.1.2.

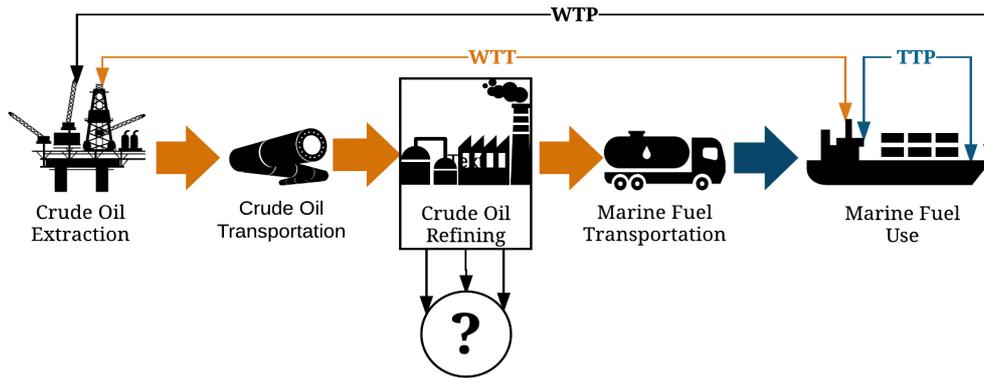


Figure 4: Illustration of a marine fuel life cycle

The framework for conducting an LCA was standardized by the International Organization for Standardization (ISO), who published two standards that provide guidance to perform a standardized LCA. The two standards are the ISO 14040 - *Principles and Framework* and the ISO 14044 - *Requirements and Guidelines* (ISO 2006b, 2006a). The structure of this study will follow the ISO 14040 and 14044, comprising the four phases that are listed below and further illustrated in Figure 5.

1. Goal and scope definition
2. Life cycle inventory (LCI)
3. Life cycle impact assessment (LCIA)
4. Interpretation

The first phase aims to define the system under study, while the second phase, has the purpose of quantify the inputs and outputs of the system in relation to its functional unit. In the third phase, LCIA, the environmental impacts of a system through its life cycle are quantified. The fourth and final phase - interpretation, aims to discuss the results obtained as a basis for conclusions and future work.

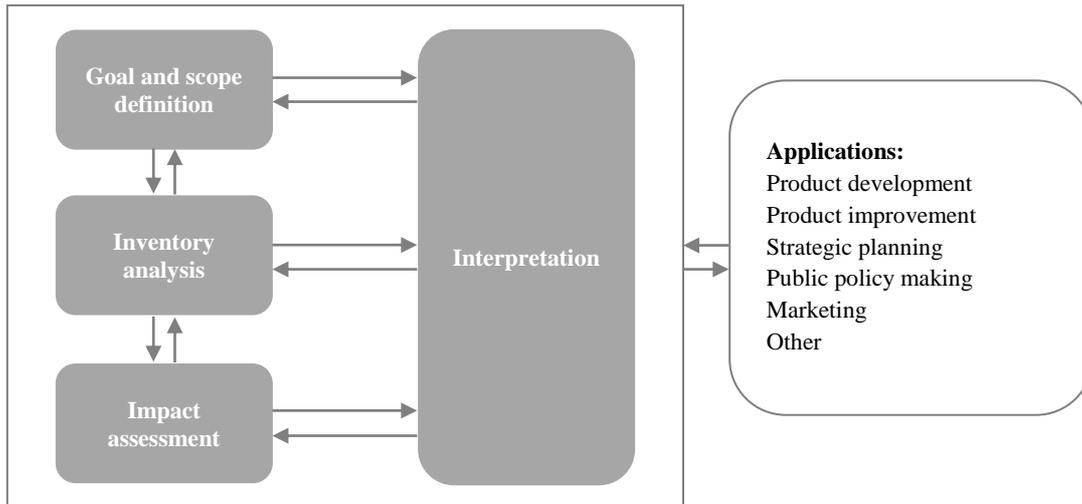


Figure 5: LCA Framework, from ISO(2006b)

As illustrated in Figure 5, the different phases are closely linked to each other. The first three phases must be carried out consecutively, while the interpretation should be performed at each phase. Nevertheless, as LCA is an interactive process, the four phases can be revised when necessary. In the following sections, a further description of each phase is performed.

3.1.1 Goal and scope definition

An LCA study starts with goal and scope definition. The goal states the purpose of the study and should clearly inform the readers about its intended application (ISO 2006b). For example, whilst some studies may aim to compare two different products that fulfill the same function, other studies may aim to evaluate which life cycle phase contributes most to the global warming impact category.

After the goal is stated, the scope of the study must be defined. The scope comprises the definition of functional unit, system boundaries, and impact categories to be considered (Baumann and Tillman 2004). The functional unit quantifies the system's performance and serves as a basis for comparison, thus reflecting the function of a product or system. Thereafter, the system boundaries should be outlined, i.e. the unit processes to be included

in the study shall be defined. Essentially, the definition of system boundaries will establish if the study follows a cradle-to-grave or a cradle-to-gate perspective, as illustrated in Figure 1, in blue and orange color, respectively. The choice of unit processes depends on the goal and scope of the study, but also on data, cost constraints and cut-off criteria (ISO, 2006a). In this sense, all assumptions made in this phase should be further considered in the interpretation phase, as they will influence the final results (ISO 2006b). Lastly, the impact categories that will be considered in the study shall be addressed.

3.1.2 Inventory analysis

The second phase of an LCA aims to quantify the inputs and outputs of a system in relation to its functional unit. The inputs are the resources used and the outputs the emissions generated. It comprises the construction of a flow model in accordance with the system boundaries defined, data collection, data documentation clearly stating and explaining the assumptions made, and, lastly, calculation of the environmental impacts (Baumann and Tillman 2004).

The flow model is usually shown as a flow diagram, where all the processes included in the analyzed system are illustrated, as well as the flows between them (Baumann and Tillman 2004). In the flowchart, processes are usually illustrated by boxes, while flows are illustrated by arrows. The flows can be substances that cause impact to the environment, such as exhaust gases from fuel combustion, or materials that were extracted from the environment, such as crude oil extracted from under the sea bed and used to produce fuel. The model is often divided into foreground and background system. The foreground system consists of processes that are modeled with specific data for the given study, while the background system consists of processes that are modeled based on generic databases and serves as input to the foreground system (Strømman 2010).

At this phase, an allocation procedure should be carried out if the system produces more than one output, in order to allocate the environmental burdens between the products. In this study, an allocation procedure is performed in the background system by using the supply use tables (SUT) framework, as further explained in Section 3.1.2.1. The mathematical basis of LCA methodology can be found in Strømman (2010).

3.1.2.1 Allocation procedure

The allocation issue is one of the most persistent methodological challenges of LCA (Finnveden et al. 2009). For example, an oil refinery produces multiple outputs, such as gasoline, diesel, jet-fuel and heavy fuel oil, among other types of petroleum products. In this sense, to know which fraction of emissions from the refinery operation and upstream environmental burdens correspond to each output, an allocation procedure should be carried out, which may constitute a challenge.

The different allocation procedures used in LCA to deal with multioutput processes have been discussed over the time (Strømman 2010; Wang et al. 2004). However, according to ISO (2006b), if allocation cannot be avoided by system expansion, for example, *partitioning approach* should be used instead. The *partitioning approach* essentially assigns a share of the total impacts by using a chosen property such as mass, or price, or other (Strømman 2010).

Due to the compatibility and complementarity of LCA and environmentally extended input-output analysis (EEIO), hybrid EEIO-LCA methods have been employed by a significant number of studies (Arvesen 2013; Crawford 2009; Hou et al. 2014). Nevertheless, a formal description of a unified framework for the treatment of coproducts is still lacking. To fill this gap, Majeau-Bettez et al. (2014) proposed a unified theory of allocations and constructs in LCA. The authors proposed a unified description of all modeling steps and assumptions necessary to go from an initial supply and use table (SUT) inventory to a system description suitable for life cycle calculations (Majeau-Bettez et al. 2014). In EEIO, the treatment of coproducts has been performed by using constructs, i.e. symmetric system descriptions, represented as product-by-product or industry-by-industry tables, from rectangular product-by-industry inventory tables (Majeau-Bettez et al. 2014). The existent types of constructs are the *commodity-technology construct* (CTC) and the *industry-technology construct* (ITC). For both, the use of commodities by activities translates in a use matrix (U), while the production of commodities by activities translates in a supply matrix (V). Taking as example the oil refinery, the inputs required for every single process considered in the refinery model should be listed in U, while the outputs should be listed in V.

After setting the U and V matrices, the next step in the framework developed by Majeau-Bettez et al. (2014) is the calculation of the partitioning coefficients for each product in each industry (Φ_j). This is calculated as follows.

$$\Phi = (\widehat{V'\Psi})^{-1}(V' * \Psi') \quad \text{Equation 1}$$

The partitioning coefficients can be based on product's mass, energy, price, or other intensive partitioning property in the partitioning property matrix Ψ . Then, by using the partitioning coefficients previously calculated, one can allocate the use of each industry (U) over all products and calculate the flow matrix (Z), as shown in Equation 2. From here, a requirements matrix A can be calculated summing the supply matrix V (or multiply by a vector of ones) and dividing Z by the diagonal of total supply vector q, as presented in equation 4.

$$Z = U\Phi \quad \text{Equation 2}$$

$$q = Vi \quad \text{Equation 3}$$

$$A = Z\hat{q}^{-1} \quad \text{Equation 4}$$

In this study, the framework proposed by Majeau-Bettez et al. (2014) is applied and further presented in Section 4.1. For further details with regards the methodology, please see the referred literature, Majeau-Bettez et al. (2014) as well as the software code published here: https://github.com/majeau-bettez/allocation_construct.

3.1.3 Impact assessment

At the third phase of an LCA, the environmental impacts of a product throughout its life cycle are quantified. It comprises the selection of impact categories to be further analyzed, categories indication and characterization methods (ISO 2006b).

This phase can be sub-divided in four steps, which are, classification, characterization, normalization, and finally, weighting (Baumann & Tillman, 2004). However, as the last two steps are considered optional, they will not be performed in this study. The goal of

classification is to sort the result parameters from the previous phase according to the type of environmental impact they contribute to. For instance, CO₂ is classified as a contributor to climate change, while NO_x is classified as a contributor to acidification. After classification, the characterization is performed. The characterization is a quantitative step where the environmental impacts are calculated per category through the utilization of equivalency factors. For example, all acidifying emissions are aggregated into one indicator for acidification, SO₂e, while for the global warming the indicator is CO₂e. Depending on the goal of the study, the characterization can either be done at a midpoint or at an endpoint level. As example, global warming can be either midpoint and endpoint level impact category. This is because global warming is by itself an environmental problem but at the same time, it contributes to endpoint level impact categories, such as human health and ecosystem damage. (Baumann and Tillman 2004)

A widely used method for quantifying environmental impacts is the ReCiPe method. This method consists of eighteen midpoint and three endpoint level categories. At the midpoint level, the LCI results are converted into category indicators, while at the endpoint level the effect of the LCI results is quantified on the three endpoint indicators. Nevertheless, it should be noted that midpoint level has associated lower uncertainty than the endpoint level, since it uses data published by IPCC and thus with higher acceptance, while the latter is based on own models and data from World Health Organization (Goedkoop et al. 2013). In addition to the different midpoint and endpoint impact categories, ReCiPe contains three different cultural perspectives – *individualist*, *hierarchist* and *egalitarian*. The perspectives differ in terms of time frame or technology development expectations, for example. Further information regarding the three cultural perspectives of ReCiPe method can be found in the literature, Goedkoop et al. (2013). In this study, the default *hierarchist* perspective will be used.

3.1.4 Interpretation

Lastly, the interpretation phase aims to provide conclusions and recommendations for environmental improvements. It should include an evaluation of the goal and scope of the study, as well as possibilities to reduce the impacts of the system analyzed on the environment (Baumann and Tillman 2004). According to ISO (2006b), a sensitivity and

contribution analysis are necessary to confirm the LCA conclusions. The sensitivity analysis aims to assess the robustness of the results, i.e. how dependent the results are on different parameters from the inventory analysis, while the contribution analysis aims to assess the contribution of each unit process in the analyzed system. It should also reflect on the assumptions made as well as on the limitations associated with the methodology, and it may also include recommendations for future work.

3.2 Tools used

Python is a widely used high-level programming language for general-purpose programming, and was used to run the framework proposed by Majeau-Bettez et al. (2014), i.e. to convert SUT tables into an A matrix.

The software Arda, version 1.8.2 was used to perform the life cycle assessment calculations. It is an LCA software developed at Industrial Ecology Department at the Norwegian University of Science and Technology. The software includes an excel sheet for modeling the foreground system that is coupled with *Ecoinvent 3.2* database. The Ecoinvent database is based on industrial data that have been compiled by internationally renowned LCA consultants and research institutes. It presents consistent, transparent, and up-to-date Life Cycle Inventory data. Furthermore, the software is integrated with the ReCiPe impact assessment methodology.

MATLAB vR2014a, a product by MathWorks, was used to run Arda, and the results were saved in excel format for further processing and layout. For all model runs the foreground inventories and raw results are available in Digital Appendix A.

4 Life cycle inventory

In this Chapter, the system under study is defined according to the system boundaries presented in Section 1.3 – Figure 1. Data collection for each phase is described, and methodological choices are explained. Regarding the background processes, unit-processes from *Ecoinvent 3.2* database are used. The inventory phase is modelled as presented in Chapter 3, and the complete LCI can be found in Digital Appendix A.

4.1 Production phase

This phase comprises the refinery construction and crude oil processing at the refinery. The refinery construction was modelled by using the unit process *petroleum refinery construction*, from *Ecoinvent 3.2*. The process refers to a refinery with an annual capacity of 1 Mton crude oil throughput and a lifetime of 30 years, comprising the production of materials and energy sources required for the construction, its associated emissions, as well as land occupation and transformation.

Regarding crude oil processing, the *Petroleum Refinery Life Cycle Inventory Model* (PRELIM), an excel-based model, was used to estimate the inflows and outflows associated with petroleum refining (Abella et al. 2016a). In PRELIM, a default refinery configuration is assigned and the results are presented by product type based on crude oil assay's properties. The model allows a significant number of options with regards to the refinery configuration, such as crude oil assay selection, process unit configuration and energy source. In this study, the selected crude oil assay was the *Norway Oseberg Statoil*, and it was assumed a natural gas fired power plant as energy source. Figure 6 presents a zoom-in to the crude oil refining unit process that comprises the system boundaries defined in Section 1.3. The flow diagram presents the processes considered in the refinery configuration as well as the main inputs and outputs of each process. Sulfur recovery process was excluded from the refinery system boundaries since it was considered out of the scope of this study. In the flow diagram, the grey dotted line refers to the system boundaries at the refinery to produce HFO, while the orange dotted line refers to LSHFO production. A detailed flow diagram can be found in Digital Appendix A.

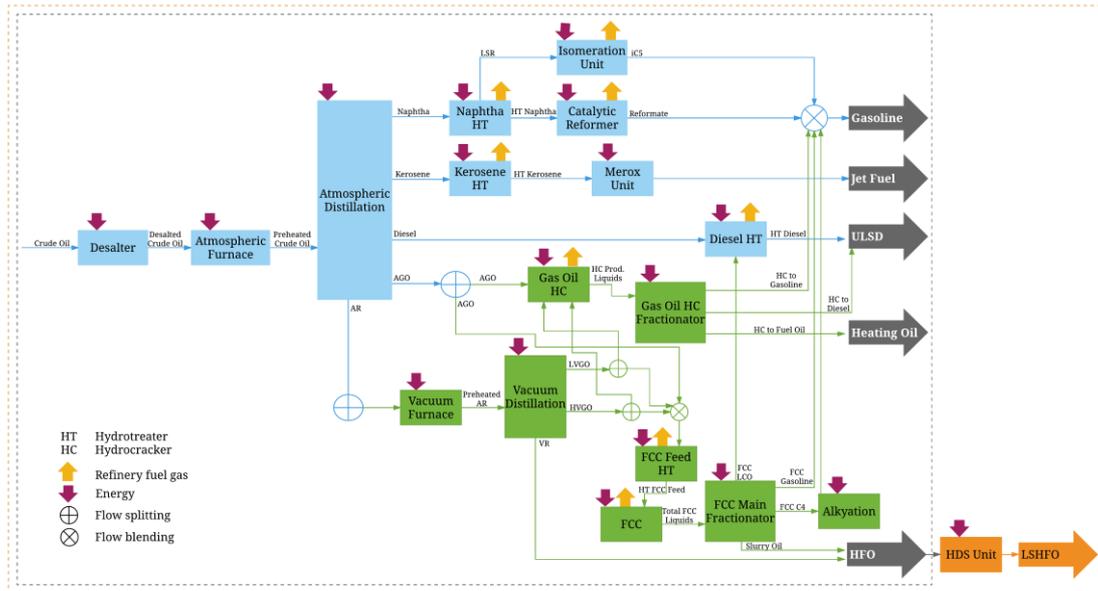


Figure 6: Refinery processes flow diagram, adapted from Abella et al. (2016b)

As *crude oil processing* is a multioutput unit process, an allocation procedure is required. The allocation method used in this study was based on the framework proposed by Majeau-Bettez et al. (2014), previously described in Section 3.1.2.1. However, instead of selecting a partitioning coefficient based on just one product’s property, the partitioning approach is based on the three most used product’s properties: mass [kg/kg], energy [MJ/kg] and price [\$/kg], as shown in Table 6. This will allow to assess whether significant changes in the total results occur when the different product’s properties are applied in the partitioning approach, thus fulfilling one of the research questions of this study, Section 1.2. It should be noted that heating oil, one of refinery’s products, is not considered in the further analysis since its mass flow is considered negligible, 1.28E-06 kg/d, when compared to the remaining refinery products.

Table 6: Main refinery product’s properties

Refinery product	Mass [kg/d]	Energy [MJ/kg]	Price [\$/kg]
Gasoline	5.52E+06	42.55	0.85
Jet-Fuel	3.02E+06	41.51	0.70
ULSD	2.29E+06	41.32	0.68
Heavy Fuel Oil	1.79E+06	39.09	0.34
LSHFO	1.79E+06	41.76	0.40

Note that the values presented in Table 6 were extracted from PRELIM model for all refinery products, excepting for LSHFO with regards to energy and price properties. For the latter, the lower heating value was taken from ERAB (ERAB 2017), whereas the price was based on an annual average taken from the daily updated Ship&Bunker website (Ship&Bunker 2017) .

Regarding the direct emission of GHGs associated with the refinery operation, PRELIM model assigns the emissions at a refinery level instead of a refining-process-level, as advocated by the International Organization for Standardization (ISO). In this sense, to allocate the emissions at a process-level, the following steps were performed. Firstly, from the United States Environmental Protection Agency website, the 2015 GHG emissions associated with the refinery industry were searched (EPA 2017b). Secondly, from the previous search the most relevant refineries were chosen, namely Philadelphia Refinery, Houston Refinery, EXXONMOBIL Baytown Refinery, and Valero Corpus Christi Refinery. Thereafter, from the *Greenhouse Gas Subpart Y Model* provided by U.S. EPA, the emissions per process per refinery for the year 2015 were taken (EPA 2017b). Lastly, the refinery capacities per process were taken from the United States Energy Information Administration (EIA 2016). By taking the emissions and the capacity per refinery per process per year, the emissions were then scaled to represent the refinery under study. As the outputs of the refinery under study were in kilograms per day, the conversion from the annual emissions was done by assuming an annual operation rate of 90%.

However, it should be noted that the *Greenhouse Gas Subpart Y Model* only provides annual GHG emissions for a limited number of refinery processes, such as catalytic reforming, fluid catalytic cracker, sulfur recovery and flares production as well as emissions associated with leaks from equipment and storage tanks, among others. From these, catalytic reforming, fluid catalytic cracker, and flares production processes were considered the most relevant ones, accounting on average for 98%, 54% and 100% for the total CO₂, CH₄ and N₂O emissions, respectively, for the chosen refineries. The direct non-GHG emissions were not estimated due to a lack of data. The annual emissions per process for the modeled refinery are presented in Table 7.

Table 7: Annual emissions per process, in kilograms per day

Process	Unit	CO ₂	CH ₄	N ₂ O
Catalytic Reforming	[kg/d]	3.85E+03	5.41E-02	1.12E-02
Fluid Catalytic Cracker	[kg/d]	3.73E+05	1.12E+01	2.24E+00
Flares	[kg/d]	3.81E+04	1.41E+03	3.81E-01

To produce LSHFO an HDS process was added to the refinery, as illustrated in Figure 6. The desulfurization process requires an energy source and consists essentially on adding hydrogen and a catalyst to the HFO feed, resulting in the emission of H₂S, further converted in sulfur through the sulfur recovery process, and in the production of LSHFO, as extensively described in Section 2.4.1. As previously stated, the sulfur recovery process was excluded from the refinery system boundaries, and thus H₂S stream was cut-out.

Hydrogen and catalyst consumption was based on the estimations of Kokayeff et al. (2015) for the desulfurization of a residual oil, whereas energy requirements were based on the energy use estimates for hydrotreatment process in U.S. refineries for year 2005 (Pellegrino et al. 2007). Energy, hydrogen and catalyst requirements for the modelled process are shown in Table 8.

Table 8: HDS process requirements

Parameter	Unit	Amount
Energy	kWh/d	6.26E+04
Hydrogen	Kg/m ³	1.02E+05
Catalyst	Kg/d	5.78E-01

The complete life cycle inventory of the modelled refinery, including SUTs, direct GHGs emission matrix, and allocation coefficients, can be found in Digital Appendix A.

4.2 Use phase

The use phase comprises the combustion of HFO and LSHFO in a Bulk Carrier and was modelled after Bouman et al. (2017). The study performs a cradle-to-grave analysis of a Bulk Carrier, comprising its construction, operation and EOL (Bouman et al. 2017). This type of vessel represents around 70.7% of the total global seaborne trade, making it one of the most important segments of maritime transport (Smith et al. 2015).

4.3 Other processes

The LCIs of crude oil extraction and transportation of marine fuels from the refinery to the vessel were modeled by using the *Ecoinvent 3.2* database. A background database was used to model these processes since it was assumed that from a life cycle perspective, they present a low contribution towards the total impacts, and therefore the development of an LCI was not prioritized.

The crude oil extraction was modelled by using the unit process *market for petroleum*, comprising oil exploration and its further transportation to the refinery. Regarding the transportation of HFO and LSHFO from the refinery to the vessel, *transport, freight, sea, transoceanic ship* was the unit process chosen. This process comprises vessel construction and its operation. It was assumed that the marine fuels were transported over 645 kilometers from the refinery to the vessel.

5 Impact assessment results

In this Chapter, the results are presented per functional unit for the environmental impact categories included in the ReCiPe method, following the ReCiPe hierarchist impact assessment model.

The results are first presented for the eighteen midpoint impact categories for the different refinery products, based on the three property-based allocations performed, i.e. mass, energy and price, in Section 5.1. This aims to provide a holistic overview of the results, providing a starting point to a further analysis. Thereafter, in Section 5.2, the impacts per refinery product and per allocation model are presented towards GWP, in order to assess if significant differences were obtained between the different property-based allocations. In Sections 5.3 and 5.4, the analysis is narrowed to the environmental impacts of HFO and LSHFO. Firstly, an analysis of the absolute contribution per process towards GWP for HFO and LSHFO is performed. Thereafter a full contribution analysis for all impact categories is presented for both HFO and LSHFO, aiming to assess if trade-offs occur between the different impact categories.

Note that the results per tkm, comprising HFO and LSHFO production, vessel construction, operation and EOL are only presented in Chapter 6, Section 6.1.

5.1 Total environmental impacts

In this section, the total environmental impacts per refinery product are presented in Tables 9, 10 and 11 for mass, energy and price-based allocation, respectively.

Table 9: Environmental impacts per kg of refinery product, mass-based allocation

Characterization Factor	Unit	Gasoline	Jet Fuel	ULSD	HFO	LSHFO
ALOP	m ² year	6.82E-03	4.18E-03	5.82E-03	3.67E-03	7.65E-03
GWP	kg CO ₂ eq.	6.24E-01	3.52E-01	4.72E-01	3.46E-01	4.82E-01
FDP	kg oil eq.	1.25E+00	1.15E+00	1.18E+00	1.14E+00	1.24E+00
FETP	kg 1.4-DB eq.	3.55E-03	2.72E-03	3.15E-03	2.59E-03	3.61E-03
FEP	kg P eq.	7.90E-05	4.80E-05	6.51E-05	4.19E-05	7.86E-05
HTP	kg 1.4-DB eq.	9.56E-02	7.19E-02	8.47E-02	6.78E-02	9.70E-02
IRP	kg U ₂₃₅ eq.	2.37E-01	2.18E-01	2.26E-01	2.16E-01	2.34E-01
METP	kg 1.4-DB eq.	2.83E-03	2.03E-03	2.45E-03	1.90E-03	2.86E-03
MEP	kg N eq.	7.61E-05	6.07E-05	6.86E-05	5.85E-05	7.80E-05
MDP	kg Fe eq.	1.42E-02	1.22E-02	1.30E-02	1.20E-02	1.42E-02
LTP	m ²	1.14E-03	1.11E-03	1.11E-03	1.11E-03	1.11E-03
ODP	kg CFC-11 eq.	6.52E-07	6.12E-07	6.23E-07	6.10E-07	6.34E-07
PMFP	kg PM ₁₀ eq.	1.08E-03	9.44E-04	1.00E-03	9.29E-04	1.06E-03
POFP	kg NMVOC	2.70E-03	2.39E-03	2.53E-03	2.37E-03	2.72E-03
TAP	kg SO ₂ eq.	3.42E-03	3.04E-03	3.20E-03	3.00E-03	3.35E-03
TETP	kg 1.4-DB eq.	2.26E-04	2.14E-04	2.18E-04	2.14E-04	2.23E-04
ULOP	m ² year	3.77E-03	3.51E-03	3.61E-03	3.50E-03	3.77E-03
WDP	m ³	1.64E-02	9.08E-03	1.33E-02	7.95E-03	1.91E-02

Table 10: Environmental impacts per kg refinery product, energy-based allocation

Characterization Factor	Unit	Gasoline	Jet Fuel	ULSD	HFO	LSHFO
ALOP	m ² year	6.86E-03	4.18E-03	5.71E-03	3.49E-03	7.46E-03
GWP	kg CO ₂ eq.	6.27E-01	3.52E-01	4.64E-01	3.28E-01	4.63E-01
FDP	kg oil eq.	1.27E+00	1.15E+00	1.16E+00	1.08E+00	1.18E+00
FETP	kg 1.4-DB eq.	3.58E-03	2.73E-03	3.08E-03	2.46E-03	3.48E-03
FEP	kg P eq.	7.94E-05	4.80E-05	6.39E-05	3.97E-05	7.65E-05
HTP	kg 1.4-DB eq.	9.65E-02	7.20E-02	8.29E-02	6.44E-02	9.36E-02
IRP	kg U ₂₃₅ eq.	2.40E-01	2.19E-01	2.21E-01	2.05E-01	2.23E-01
METP	kg 1.4-DB eq.	2.85E-03	2.04E-03	2.40E-03	1.81E-03	2.77E-03
MEP	kg N eq.	7.68E-05	6.08E-05	6.71E-05	5.55E-05	7.50E-05
MDP	kg Fe eq.	1.43E-02	1.22E-02	1.27E-02	1.13E-02	1.36E-02
LTP	m ²	1.15E-03	1.11E-03	1.08E-03	1.05E-03	1.06E-03
ODP	kg CFC-11 eq.	6.61E-07	6.13E-07	6.08E-07	5.79E-07	6.03E-07
PMFP	kg PM ₁₀ eq.	1.09E-03	9.46E-04	9.81E-04	8.82E-04	1.01E-03
POFP	kg NMVOC	2.74E-03	2.40E-03	2.47E-03	2.25E-03	2.60E-03
TAP	kg SO ₂ eq.	3.46E-03	3.04E-03	3.13E-03	2.84E-03	3.20E-03
TETP	kg 1.4-DB eq.	2.29E-04	2.15E-04	2.13E-04	2.03E-04	2.12E-04
ULOP	m ² year	3.82E-03	3.52E-03	3.53E-03	3.32E-03	3.60E-03
WDP	m ³	1.64E-02	9.10E-03	1.31E-02	7.55E-03	1.87E-02

Table 11: Environmental impacts per kg refinery product, price-based allocation

Characterization Factor	Unit	Gasoline	Jet Fuel	ULSD	HFO	LSHFO
ALOP	m ² year	7.77E-03	4.09E-03	5.48E-03	2.46E-03	6.43E-03
GWP	kg CO ₂ eq.	7.11E-01	3.44E-01	4.50E-01	2.27E-01	3.62E-01
FDP	kg oil eq.	1.49E+00	1.12E+00	1.12E+00	7.65E-01	8.63E-01
FETP	kg 1.4-DB eq.	4.13E-03	2.66E-03	2.97E-03	1.74E-03	2.76E-03
FEP	kg P eq.	8.99E-05	4.70E-05	6.15E-05	2.80E-05	6.47E-05
HTP	kg 1.4-DB eq.	1.11E-01	7.02E-02	7.99E-02	4.54E-02	7.46E-02
IRP	kg U ₂₃₅ eq.	2.81E-01	2.13E-01	2.14E-01	1.45E-01	1.63E-01
METP	kg 1.4-DB eq.	3.27E-03	1.99E-03	2.31E-03	1.27E-03	2.23E-03
MEP	kg N eq.	8.89E-05	5.92E-05	6.47E-05	3.92E-05	5.87E-05
MDP	kg Fe eq.	1.67E-02	1.18E-02	1.23E-02	8.02E-03	1.03E-02
LTP	m ²	1.36E-03	1.08E-03	1.05E-03	7.45E-04	7.49E-04
ODP	kg CFC-11 eq.	7.76E-07	5.96E-07	5.88E-07	4.10E-07	4.33E-07
PMFP	kg PM ₁₀ eq.	1.28E-03	9.20E-04	9.47E-04	6.23E-04	7.54E-04
POFP	kg NMVOC	3.20E-03	2.33E-03	2.38E-03	1.59E-03	1.94E-03
TAP	kg SO ₂ eq.	4.04E-03	2.96E-03	3.02E-03	2.01E-03	2.37E-03
TETP	kg 1.4-DB eq.	2.69E-04	2.09E-04	2.06E-04	1.44E-04	1.53E-04
ULOP	m ² year	4.48E-03	3.42E-03	3.41E-03	2.35E-03	2.62E-03
WDP	m ³	1.85E-02	8.89E-03	1.26E-02	5.31E-03	1.65E-02

The results show that refining process presents higher impact towards GWP and fossil depletion potential (FDP). These results are expected since the main inputs of the refinery are crude oil, which extraction is the main contributor towards FDP, and energy sources, such as natural gas, electricity, and steam, which production contributes greatly to GWP. In addition, the refining process also contributes significantly to other impact categories such as human toxicity potential (HTP), and terrestrial acidification potential (TAP). For both, the main contributor processes are the extraction of crude oil and the production of energy sources that are required during the operation of the refinery, leading to discharges to water, soil and air. Impacts towards agricultural and urban land occupation potential (ALOP and ULOP) are also considered relevant, being the former mainly associated with the extraction of crude oil, and the later with the construction of the refinery site. A further analysis of the contribution per process per impact category for HFO and LSFO is presented in Section 5.4.

Results also show minor differences between the different allocation models, which are further discussed in Sections 5.2 and 5.3. Nonetheless, it is important to notice that regardless of the allocation model, gasoline and LSHFO are the refinery products that most contribute to the total impacts. Gasoline is the major refinery output, i.e., it is produced in much higher quantities when compared to the remaining fuels, and in addition, it presents the highest market price and energy content among the refinery products. Therefore, it is expected its high contribution to the total impacts. On the other hand, LSHFO has the second highest energy content, making it one of the main contributors to the total impacts when considering energy-based allocation. However, in terms of mass and price, it presents relatively lower values when compared to gasoline and ULSD, as shown in Table 5, Section 4.1. At the same time, it requires much higher quantities of energy and hydrogen than the remaining refinery products due to the sulfur removal through HDS process, thus explaining its contribution to the total impacts.

5.2 GWP per fuel type

This section aims to assess whether significant differences occur in total results when different property-based allocations are applied. In this sense, Figure 7 presents the total impacts of the different fuel types towards GWP according to the allocation model.

The selection of GWP impact category, to illustrate and further analyze the differences between the allocation models considered, has associated two main reasons: it is one of the main impact categories to which the refining process contributes to, as shown in Section 5.1, and, as stated in Sections 1.2 and 1.3, it is one of the impact categories to which maritime transport is striving to find measures to decrease its impacts.

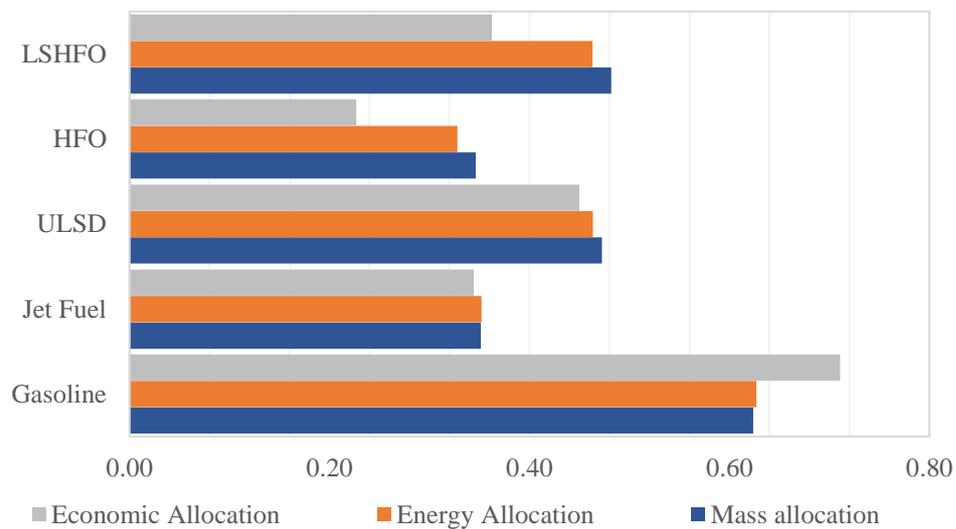


Figure 7: Total impact for GWP, in kg CO₂e per kg fuel type per allocation model

According to results, gasoline is the refinery output that contributes most towards GWP when compared to the remaining refinery products, regardless of the allocation model used. The second greater contributor is LSHFO with regards mass and energy-based allocations, being ULSD the second greater contributor towards GWP for price-based allocation.

In addition, results show that mass-based allocation presents higher impacts than energy and price-based allocations, except for gasoline. For gasoline, price-based allocation is the one with higher impacts, which is associated to its high price in the market, 0.85\$/kg.

From the refinery products, HFO is the one that presents higher differences between the different allocation models considered, closely followed by LSHFO. HFO mass-based allocation presents 5% and 35% higher impacts towards GWP than energy and price-based allocation, respectively. On the other hand, LSHFO mass-based allocation presents 4% and 25% higher impacts than energy and price-based allocations.

5.3 Comparison between HFO and LSHFO

To further analyze the differences in results associated with the different allocation models towards GWP, Figures 8 and 9 present the contribution per process and per allocation model for HFO and LSHFO.

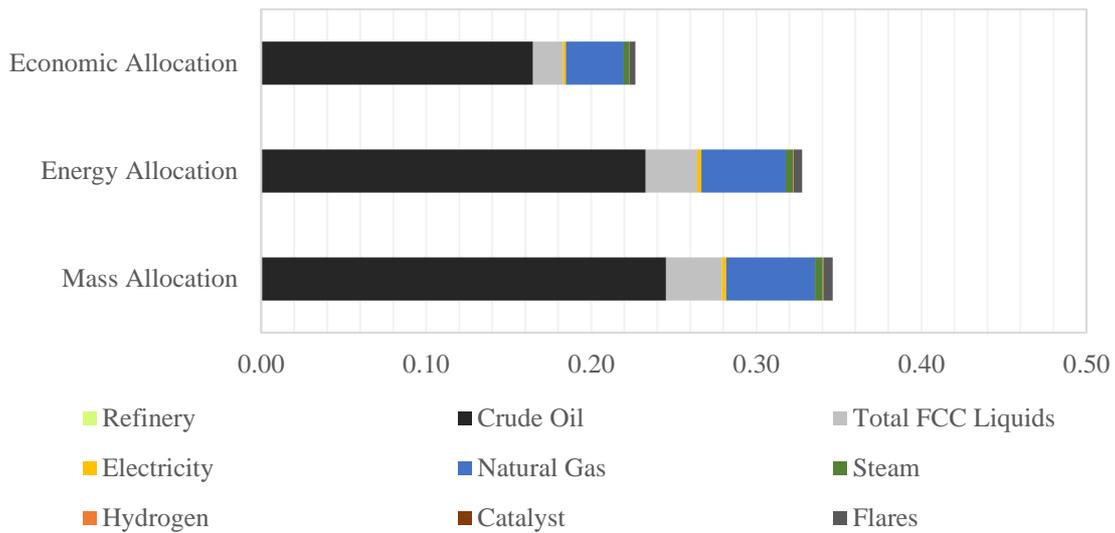


Figure 8: Contribution analysis for GWP, in kg CO₂e per kg HFO

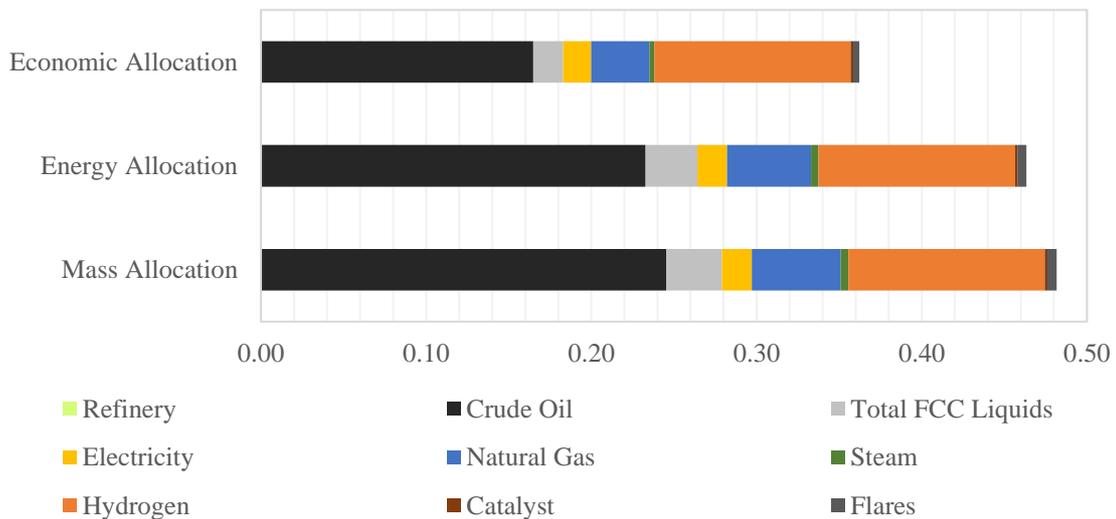


Figure 9: Contribution analysis for GWP, in kg CO₂e per kg LSHFO

According to Figures 8 and 9, crude oil extraction is the process that contributes most for GWP, regardless of the allocation model. However, its contribution and the contribution

of the remaining processes differ considerably between HFO and LSHFO as well as between the allocation models considered.

Considering HFO, crude oil extraction represents between 48% to 71% of the total impacts towards GWP, being the lowest share obtained by economic allocation and the highest by mass allocation. The process with the second higher contribution is natural gas production, which share ranges from 10% to 16% of the total impacts. Another important contribution for the total impacts towards GWP is associated with the FCC unit and the emissions that comes from it, presenting a contribution between 5% and 10%, depending on the allocation model.

Regarding LSHFO, it differs from HFO mainly due to the hydrogen production process, which in this case presents the second highest contribution towards GWP. Regardless the allocation model considered, hydrogen production accounts for 25% of the total impacts, while natural gas production only accounts for 11% considering mass and energy-based allocations, or 7% if price-based allocation is considered. Electricity production also presents an increased contribution, representing approximately 4% of the total impacts for LSHFO, while for HFO it accounts for less than 1%. As stated previously, these increases in electricity and hydrogen contributions results from the HDS unit.

5.4 Full contribution analysis for all impact categories

From the analysis of Section 5.2, energy-based allocation was selected to perform a further contribution analysis for all impact categories, for both HFO and LSHFO. The reason to select energy-based allocation is associated with the fact that it represents an average of impacts when mass and price-based allocations are considered. Furthermore, previous LCA studies on the topic of marine fuels used energy-based allocation to allocate the emissions to the different refinery products, as referred in Section 2.5, thus allowing a further comparison of results.

For both HFO and LSHFO, crude oil extraction is the process that contributes most to the total impacts, as concluded in Section 5.3. However, to better illustrate and quantify the

relative contribution of the remaining processes, crude oil extraction was excluded from Figures 10 and 11.

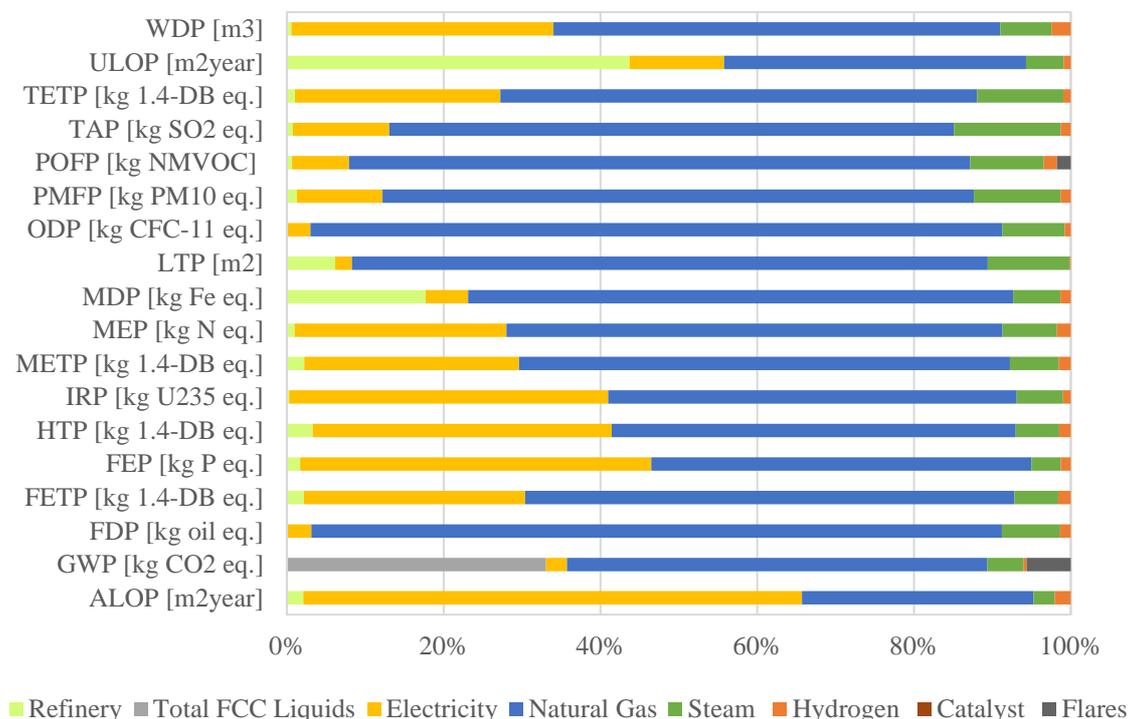


Figure 10: Relative contribution per kg HFO, excluding crude oil extraction

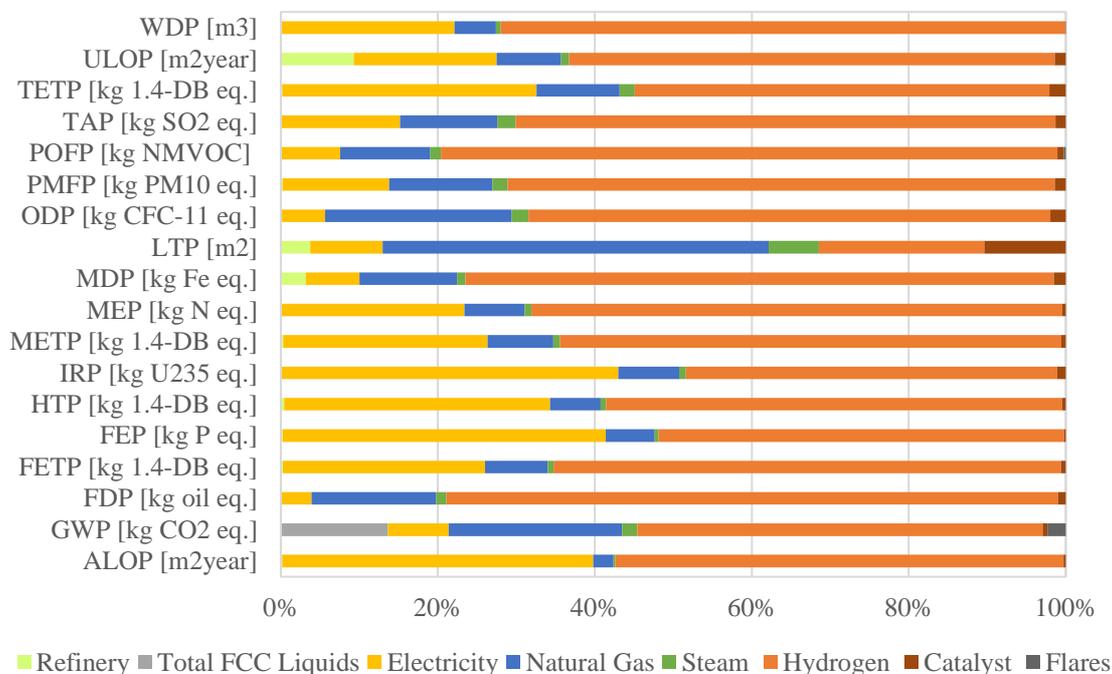


Figure 11: Relative contribution per kg LSHFO, excluding crude oil extraction

In overall, by excluding crude oil extraction, results show that for HFO, electricity and natural gas production are the main contributors towards the total impacts, regardless the impact category considered. On the other hand, for LSHFO hydrogen and electricity production are the main contributors, with natural gas production presenting a small share of impacts for most of the impact categories. These results are expected since HDS process represents an increase of approximately 12% and 46% of electricity and hydrogen consumption at the refinery, respectively, thus resulting in an increased contribution to the total impacts.

As discussed, natural gas, electricity and hydrogen production are, after crude oil extraction, the major contributors for the total results for all impact categories considered. However, to further understand the impacts associated with the refining process, a contribution analysis per stressor is thereafter presented for some impact categories.

Figures 12, 13 and 14 present a contribution analysis per stressor towards HTP, TAP and particulate matter formation potential (PMFP), respectively. These impact categories were selected since they were considered the most relevant ones at the refining phase, after GWP and FDP. The analysis includes the stressors that are contributing to more than 5% of the total impacts. Note that a contribution analysis per stressor is not performed for FDP neither for GWP since these impact categories have essentially one main contributor, petroleum production and CO₂ emissions, respectively.

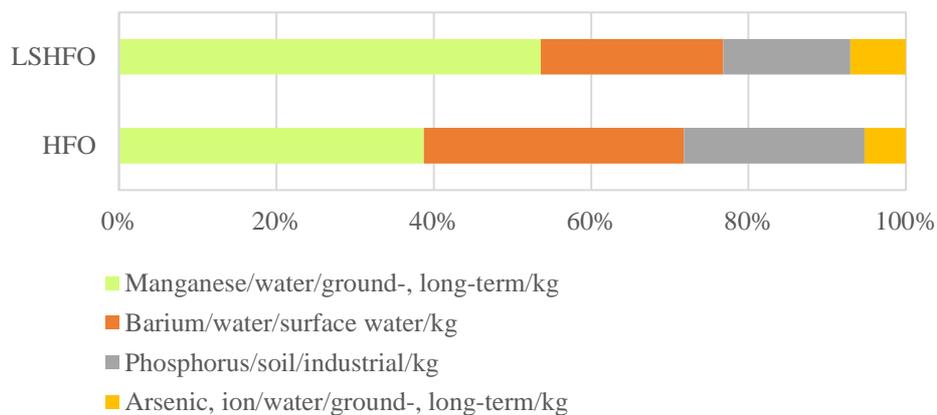


Figure 12: Contribution per stressor for HTP per kg fuel

Results show that for both HFO and LSHFO, manganese is the most contributing stressor for the total impacts towards HTP. Important to notice that all these stressors are in a larger extent associated with the extraction of crude oil.

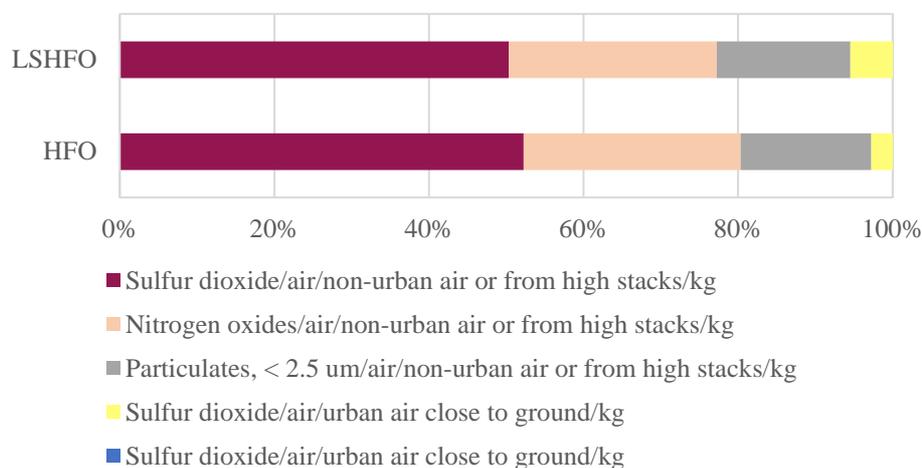


Figure 13: Contribution per stressor for PMFP per kg fuel

As shown, the most contributing stressor for the total impacts towards PMFP is sulfur dioxide (SO₂) emission, followed by NO_x emission, for both HFO and LSHFO. These stressors, are mainly linked to the use of natural gas and hydrogen, required for the refining process of HFO and LSHFO, and to a smaller extent, to the use of electricity. They are also linked to the transport of crude oil to the refinery.

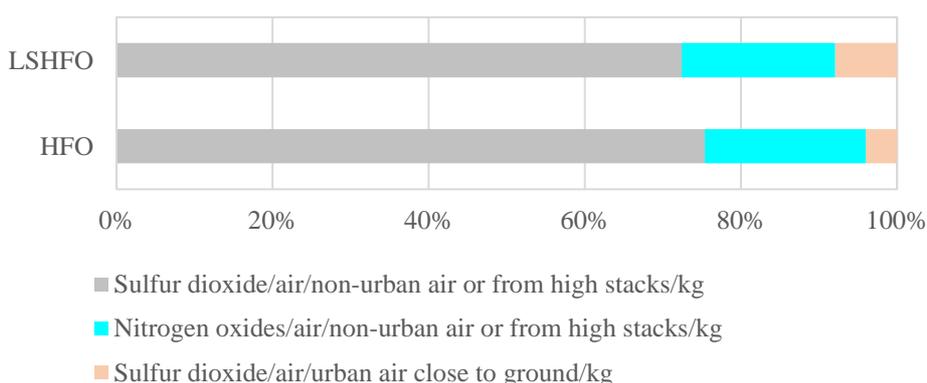


Figure 14: Contribution per stressor for TAP per kg HFO and LSHFO

According to results, SO₂ and NO_x are the main contributors towards TAP for both HFO and LSHFO. Once more, these contributions are mainly associated with the use of natural

gas and hydrogen during the refining process and to a smaller extent, they are also associated with the transportation of crude oil to the refinery site.

Other impact categories that are also considered relevant are ULOP and ALOP. For ULOP, refinery construction presents the highest impact followed by natural gas production, considering HFO. On the other hand, for LSHFO, refinery construction represents a small share of contribution by comparison, with hydrogen production presenting the highest share of impacts towards ULOP. The stressors with a contribution higher than 5% towards ULOP are illustrated in Figure 15.

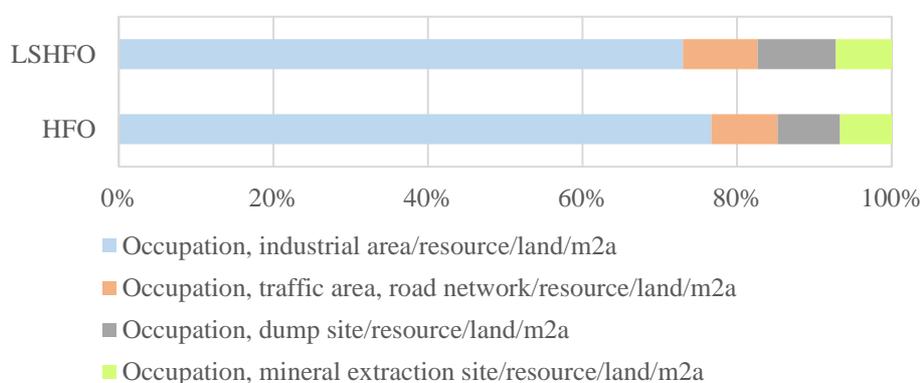


Figure 15: Contribution per stressor for ULOP per kg HFO and LSHFO

As illustrated, the occupation of industrial area is the most important stressor, accounting to more than 70% for both HFO and LSHFO, which is mainly due to onshore production plants.

On the other hand, for ALOP, electricity presents the highest share of impacts for HFO, while for LSHFO hydrogen production is the main contributing process. The of stressors contribution accounting for more than 5% is shown in Figure 16.

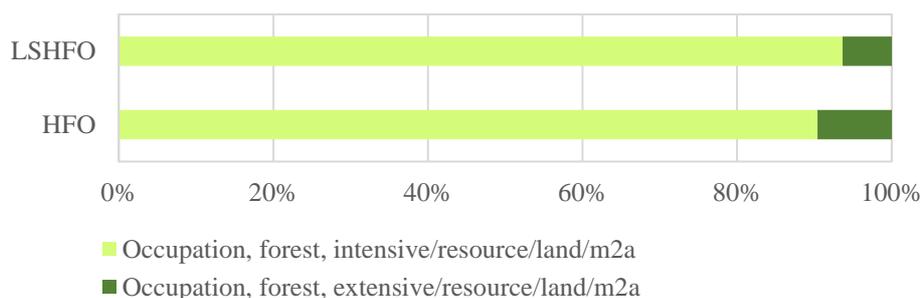


Figure 16: Contribution per stressor for ALOP per kg HFO and LSHFO

According to results, the occupation of forest is clearly the main stressor related to ALOP. It can be also noticed that the contribution among stressors is to a small extent higher for LSHFO due to its higher energy requirements.

6 Discussion

This chapter is further divided into four main sections. In Section 6.1, an analysis of the impacts over a life cycle perspective is presented, allowing a comparison between this study results and previous research within the topic of LCA of marine fuels. Therefore, in Section 6.2 a comparison with previous research results is performed. It was done according to the functional units considered in this study. In this sense, the results per kg of refinery product and per tkm were compared against other studies in order to assess if this study results are in accordance with previous research or if they rather differ significantly. Thereafter, a sensitivity analysis is performed in Section 6.3 to the variables that were considered most relevant in terms of associated uncertainty. Lastly, in Section 6.4 suggestions for further research are provided. The complete data sets and results from this chapter can be found in the Digital Appendix A.

6.1 Evaluation of the impacts over a life cycle perspective

In this section, an assessment of the impacts associated with marine fuel production is performed from a life cycle perspective. Therefore, it comprises all life cycle phases, from the extraction of crude oil, through marine fuel production and its further transportation, ship construction and operation to ship EOL.

The operation phase considers the combustion of both HFO and LSHFO, allowing to assess if there are trade-offs between the different impact categories as well as if LSHFO is a promising solution to decrease emissions of maritime sector. Regarding the impacts associated with the refining phase, energy-based allocation was the allocation model chosen to allocate the emissions that occurred during this stage. This was done based on the reasons previously stated in Section 5.4.

Table 12 presents the environmental impacts per tkm, by considering the use of HFO and LSHFO during the operation phase as well as the percentual change associated with the shift from HFO to LSHFO.

Table 12: Environmental impacts per tkm, by using HFO and LSHFO

Characterization factor	Unit	HFO	LSHFO	Deviation
ALOP	m ² year	9.91E-06	1.25E-05	26%
GWP	kg CO ₂ eq.	3.27E-03	3.33E-03	2%
FDP	kg oil eq.	1.02E-03	1.05E-03	3%
FETP	kg 1.4-DB eq.	9.09E-06	9.63E-06	6%
FEP	kg P eq.	2.26E-07	2.50E-07	10%
HTP	kg 1.4-DB eq.	2.89E-04	3.04E-04	5%
IRP	kg U ₂₃₅ eq.	1.96E-04	1.99E-04	1%
METP	kg 1.4-DB eq.	8.79E-06	9.29E-06	6%
MEP	kg N eq.	2.90E-06	2.90E-06	0%
MDP	kg Fe eq.	2.78E-04	2.79E-04	0%
LTP	m ²	9.65E-07	9.14E-07	-5%
ODP	kg CFC-11 eq.	5.26E-10	5.20E-10	-1%
PMFP	kg PM ₁₀ eq.	4.20E-05	3.39E-05	-19%
POFP	kg NMVOC	8.04E-05	7.71E-05	-4%
TAP	kg SO ₂ eq.	8.53E-05	4.51E-05	-47%
TETP	kg 1.4-DB eq.	2.20E-07	2.15E-07	-2%
ULOP	m ² year	6.88E-06	6.58E-06	-4%
WDP	m ³	3.03E-05	3.72E-05	23%

Results show that the shift from HFO towards LSHFO presents trade-offs between the impact categories. In terms of impacts on the climate, LSHFO presents a worse environmental performance than HFO, leading to an increase of approximately 2% for GWP. This is associated with the increased requirements of energy and hydrogen to produce LSHFO, as discussed in Section 5.3. The same occurs with regards ALOP and WDP, presenting an increase of 26% and 23%, respectively, when compared to HFO. Both are associated with the increased production of energy sources required to produce LSHFO. WDP can be of high concern, if regionalization is considered and if water scarcity index is high. Another concern associated with the combustion of LSHFO is that it also contributes to an increase of impacts towards FEP, thus leading to an increased eutrophication of freshwater bodies and its associated consequences, as explained in Section 2.1.

On the other hand, the use of LSHFO can lead to a significant reduction of impacts towards TAP, more specifically, a 47% reduction, which is due to the reduced sulfur content of the fuel. Moreover, LSHFO use leads to a decrease of 19% of impacts towards

PMFP. This decrease is directly linked with TAP decrease since its main stressors, SO₂ and NO_x, are responsible for the formation in the air of fine particulate matter with a diameter of less than 10µm (PM₁₀) (Lopez 2006). Decreases in impacts for ODP, POFP and FETP are also observed but to a lower extent.

To further understand the impacts from a life cycle perspective, i.e. which life cycle phase is the most relevant in terms of impacts and if there are trade-offs between the different phases, Figures 17 and 18 present the total impacts per tkm in terms of relative contribution of each life cycle phase.

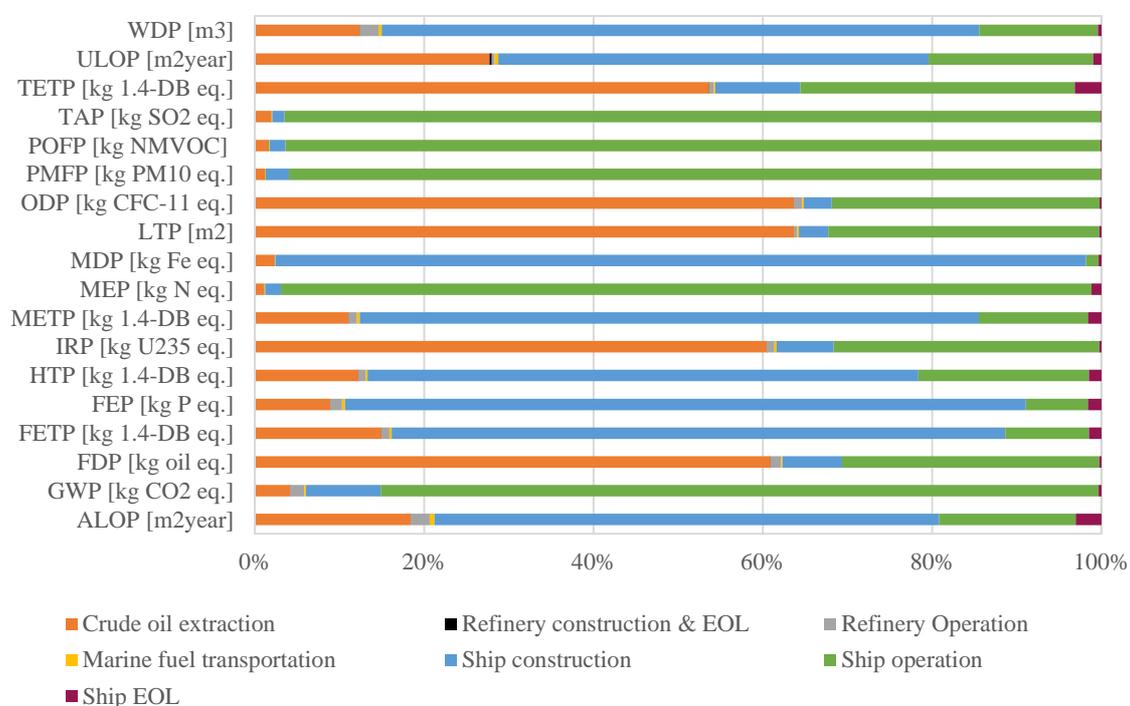


Figure 17: Environmental impacts per tkm, HFO

In overall, crude oil extraction, ship construction and ship operation are the life cycle phases that contribute most to the total environmental impacts. For GWP, ship operation accounts for 84.8%, followed by ship construction which only accounts 8.8%. Regarding MEP and TAP, the two other impact categories to which maritime transport is striving to decrease its impacts, ship operation accounts for 95.7% and 96.4% of the total impacts, respectively. In this sense, the contribution of the remaining life cycle phases can be considered negligible as they represent less than 5% of the total impacts for both MEP and TAP.

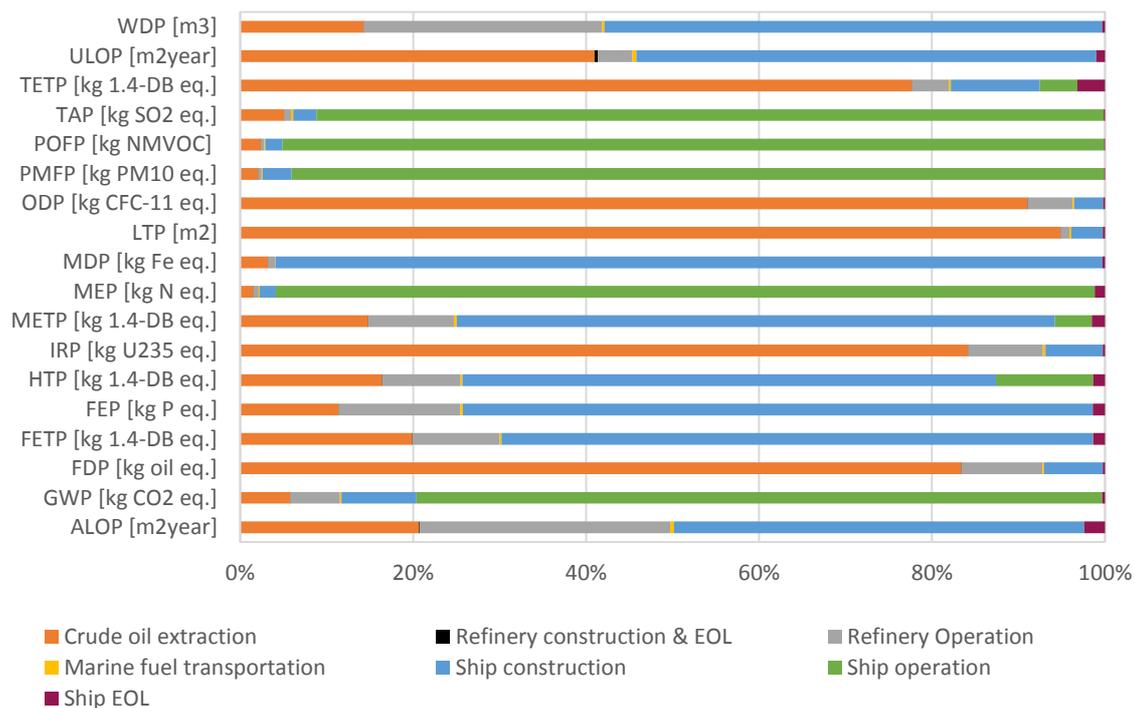


Figure 18: Environmental impacts per tkm, LSHFO

The difference in results between HFO and LSHFO are mainly associated with refinery operation phase, which presents a higher contribution for LSHFO, with a consequent decrease of ship operation contribution.

By analyzing the relative contribution of each phase towards GWP, ship operation decreases from 84.8% to 79.3% when a shift towards LSHFO is performed. Refinery operation, on the other hand, increases from 1.7% to 5.7%. In this sense, it can be concluded that the increase towards GWP (2%) occurs upstream, during the refining process of LSHFO due to higher energy and hydrogen requirements, being partly offset during the operation phase.

6.2 Comparison with previous research results

This section presents a comparison between this study key results and previous research within the field of life cycle assessment of marine fuels. Section 6.2.1 presents a comparison per kg of refinery product, while in Section 6.2.2 the functional unit of one tkm travelled is used as a basis for comparison with previous studies.

6.2.1 Comparison based on one kg of refinery product

From the studies reviewed in Section 2.5, none developed a life cycle inventory for the refining process but rather used background processes from databases such as *Ecoinvent* and *ELCD*. Therefore, from *Ecoinvent 3.2* the unit process *market for heavy fuel oil (3.5wt.% S)* was chosen as a basis for comparison while from *ELCD* the process *heavy fuel oil at refinery (1.0wt.% S)* was selected. Both processes comprise the extraction of crude oil, its further transportation to the refinery site and the refining of crude oil to produce one kg of HFO. *Ecoinvent* also comprises the further transportation of HFO until its final consumer. Furthermore, both use energy-based allocation at the refinery. However, while from *Ecoinvent 3.2* one can obtain the impacts associated with the production of one kg of HFO per impact category, from *ELCD* one obtain the results per elementary flow, which need to be further grouped into impact categories by using characterization factors.

In this sense, the results of this study are compared to *Ecoinvent* process for all impact categories as presented in Figure 19, for one kg of HFO, while for *ELCD* only a GWP is considered.

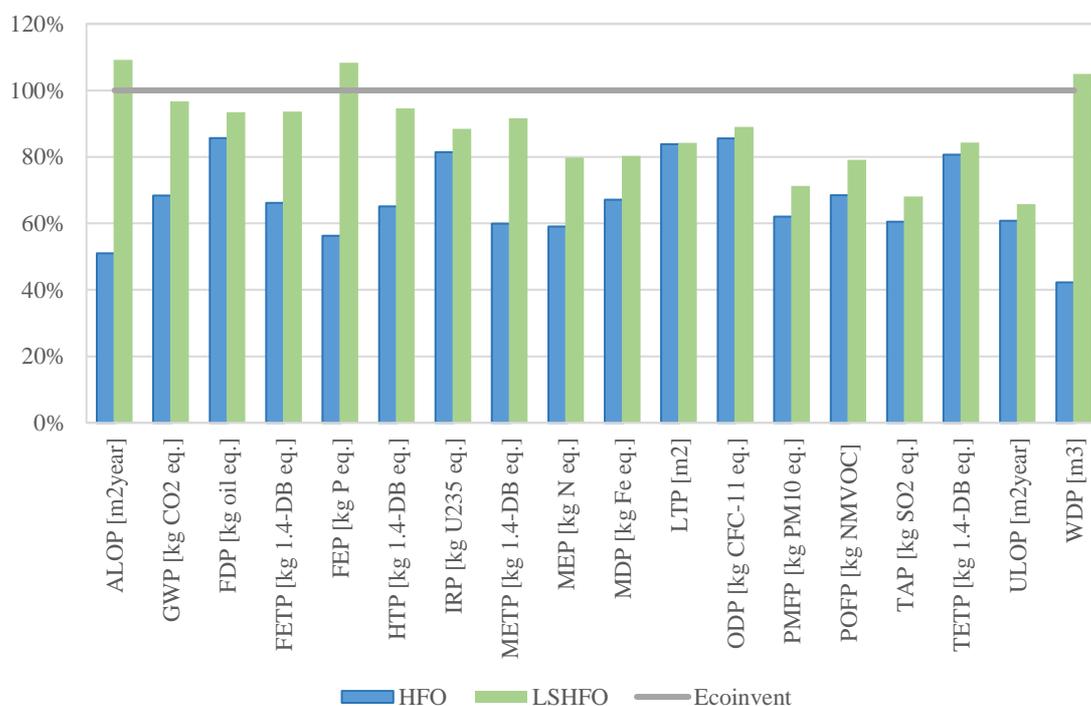


Figure 19: Results comparison with *Ecoinvent*, per kg fuel

According to Figure 19, *Ecoinvent* presents significantly higher results for all impact categories when compared with this study for HFO. For GWP, for example, *Ecoinvent* presents an impact of 4.79E-01 kg CO₂e per kg HFO against 3.28E-01 kg CO₂e per kg HFO obtained in this study, a change of 46%. This might be explained by the fact that the *Ecoinvent* process also comprises the distribution of HFO until its final consumer, including all necessary transports, while this study presents the results per kg HFO at the refinery gate. HFO transportation from the refinery gate until the vessel presented negligible contributions, as discussed in Section 6.1, but it only assumed a transportation of HFO over 645 km through a transoceanic tanker. On the other hand, *Ecoinvent* considers several modes of transport used for the distribution and transportation of HFO, such as train, barge tanker, lorry and transoceanic tanker as well as onshore pipeline. Therefore, by considering the construction, operation, dismantling and further EOL of so many transportation modes, it is expected a significant increase towards the total impacts, being thus considered plausible the differences in results obtained between this study and *Ecoinvent*. With regards the differences obtained between LSHFO and *Ecoinvent* HFO, they are significantly lower for most of the impact categories. It should be noted however that LSHFO presents a sulfur content of 0.1% while *Ecoinvent* HFO presents a sulfur content of 3.5% thus presenting lower energy requirements.

Regarding *ELCD*, the elementary flows of CO₂, CH₄ and N₂O were considered and by using characterization factors for GWP after IPCC 2013 (Myhre et al. 2013), an impact of 4.28E-01 kg CO₂e per kg HFO was obtained. Do to the fact that *ELCD* HFO presents a sulfur content of 1.0% it is more feasible to compare it with the results obtained for LSHFO in this study, than for HFO. For LSHFO an impact of 4.63E-01 kg CO₂e per kg LSHFO for GWP was obtained, thus being in high accordance with the results obtained by *ELCD*.

6.2.2 Comparison based on one tkm travelled

A limited number of LCA studies have been performed on marine fuels, as shown in Section 2.5. From the studies considered and analyzed in the referred section, differences in goal and scope were observed, thus not allowing a direct comparison between studies results.

However, in order to assess if this study results differ considerably from previous research, the key methodological aspects presented in Table 5, Section 2.5.2 were taken into account and two studies were selected, Brynolf et al. (2014) and Bengtsson et al. (2011).

The choice of these studies is mostly associated with the functional unit. Both present the impacts per tkm, the functional unit chosen in this study to assess the impacts associated with HFO and LSHFO over a life cycle perspective. In addition, both studies aim to compare the environmental performance of marine fuels, which is in accordance with the goal of this study, which aims to compare HFO and LSHFO environmental performance. With regards system boundaries, both studies did not consider the construction, dismantling and further EOL of capital goods, such as the vessel, which was considered in this study, as presented in Section 1.2. Moreover, the referred studies used the *ELCD* to calculate the impacts of HFO upstream the use phase, thus assuming a HFO with a sulfur content of 1.0%. This study, on the other hand, developed an LCI for the refining process in order to model HFO and LSHFO with a sulfur content of 3.5% and 0.1%, respectively. Considering the differences between this study and the studies considered, differences in results are thus expected to occur.

In the next sections, differences between this study results and the referred studies are presented with regards GWP and TAP.

6.2.2.1 Global Warming Potential

In this section, differences between studies results are presented both in terms of relative contribution of the two main life cycle phases – WTT and TTP, and absolute contribution from a life cycle perspective – WTP. Figure 20 presents the relative contribution of WTT and TTP for GWP, while Figure 21, presents the results in terms of absolute contribution of WTP towards GWP.



Figure 20: WTT and TTP relative contribution for GWP, in kg CO₂e per tkm

Results show that for HFO, WTT phase presents a contribution to less than 10% towards the total impacts, which differs from the studies considered. This result can be explained by the fact that the HFO considered in this study presents a sulfur content of 3.5%, thus requiring less energy and hydrogen use for the sulfur removal, subsequently leading to lower impacts at the WTT phase. The same principle can be used to explain the higher contribution of TTP phase for LSHFO. As LSHFO presents a sulfur content of 0.1%, when it is compared with HFO with a sulfur content of 1.0% it is expected that the former presents higher results due to higher energy requirements associated with the sulfur removal.

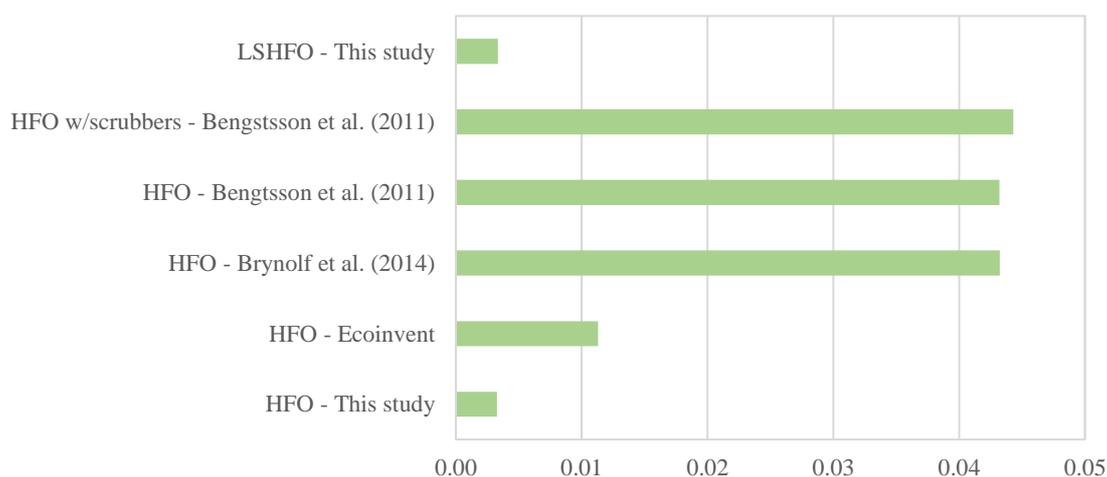


Figure 21: WTP life cycle impacts for GWP, in kg CO₂e per tkm

As shown in Figure 21, the results obtained in this study differ greatly from the Bengtsson and Brynolf studies, and present also lower impact when compared to *Ecoinvent* results. Nonetheless, a further analysis of the scope might explain such differences. Bengtsson

and Brynolf studies considered a RoPax vessel with a cargo capacity of 15 000 tons and 7 500 tons, respectively, with the modeled RoPax presenting an efficiency of 0.0568 kWh per tkm. In this study, a Bulk Carrier was considered instead, with a cargo capacity of 119 613 tons, and an efficiency of 0.00286 kWh per tkm. Therefore, the modeled Bulk Carrier presents an increase in efficiency of around 95%, thus requiring less fuel per tkm, leading subsequently to lower emissions per tkm. In addition, the emission factors used to model the Bulk carrier operation are based on EMEP/EEA 2016 Air Pollutant Emissions Inventory Guidebook (Trozzi et al. 2016), while the referred studies are based on older data.

The process *transport, freight, sea, transoceanic ship* from *Ecoinvent* was also considered, as it assesses the life cycle impacts of a Bulk Carrier with 50 000 ton of cargo capacity by using HFO with a sulfur content of 3.5% during the operation phase. The total impacts towards GWP, obtained in this study 3.27E-03 kg CO₂e per tkm, considering the use of HFO, are lower when compared to the total impact reported by *Ecoinvent* of 1.13E-02 kg CO₂e per tkm. Once more, the difference in results are mainly associated with differences at the operational phase modeling, since this study used state-of-the-art engine fuel consumption and emission factors data. Besides, due to economy-of-scale effects, the vessel considered in this study presents a much higher cargo capacity than the vessel modeled by *Ecoinvent*.

6.2.2.2 Terrestrial Acidification Potential

In overall, LSHFO has a better environmental performance towards TAP than HFO due to its lower sulfur content. As presented in Section 6.1, the increased impacts at the refining phase, due to higher energy and hydrogen consumptions, are offset at the operation phase due to the lower sulfur content of the LSHFO, leading consequently to lower impacts towards TAP. However, it should be noticed that the market provides another option to decrease sulfur emissions during the operation phase – the use of exhaust gas scrubbers, as referred in Chapter 1. Scrubbing is a space and resource consuming technique that allows the reduction of sulfur emissions to approximately 0.1%, thus complying with IMO regulations (Van Rynbach et al. 2015). A drawback associated with the use of scrubbers is that it increases the fuel consumption (Bengtsson

et al. 2011; Van Rynbach et al. 2015) and according to Bengtsson et al. (2011), it also represents a significant investment for the ship owner, but on the other hand, it enables the use of the relatively cheap HFO.

In order to compare this study results with previous research findings for TAP, two types of fuels were considered, HFO with scrubbers and MGO, both assessed by Bengtsson et al. (2011). The former was chosen due to the previously stated reasons, while the later was chosen due to the fact that it also presents a sulfur content of 0.1%, thus constituting an option to the other alternatives. In addition, the HFO assessed by Bengtsson et al. (2011) was also considered in order to assess if significant differences were obtained between HFO and HFO combustion with scrubbers over life cycle perspective - WTP.

Figure 22 compares the findings from the previous studies with this study according to the relative contribution of WTT and TTP life cycle phases towards TAP, and Figure 23 presents the impacts for TAP from a WTP perspective.

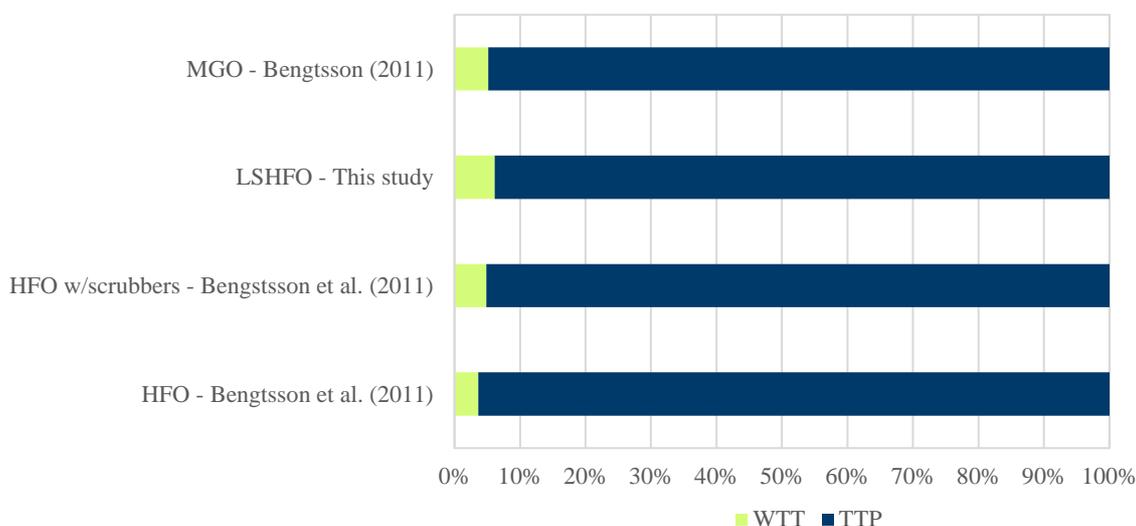


Figure 22: WTT and TTP relative contribution for TAP, in kg SO_{2e} per tkm

Results show minor differences between the studies considered and this study. The WTT phase contributes from 3.6% to 6.1% to the total results towards TAP, with HFO production presenting the lowest share and LSHFO the highest share. Regarding the TTP phase, the contributions varies from 93.9% to 96.4%, being LSHFO the one with the lowest contribution and HFO with the highest.

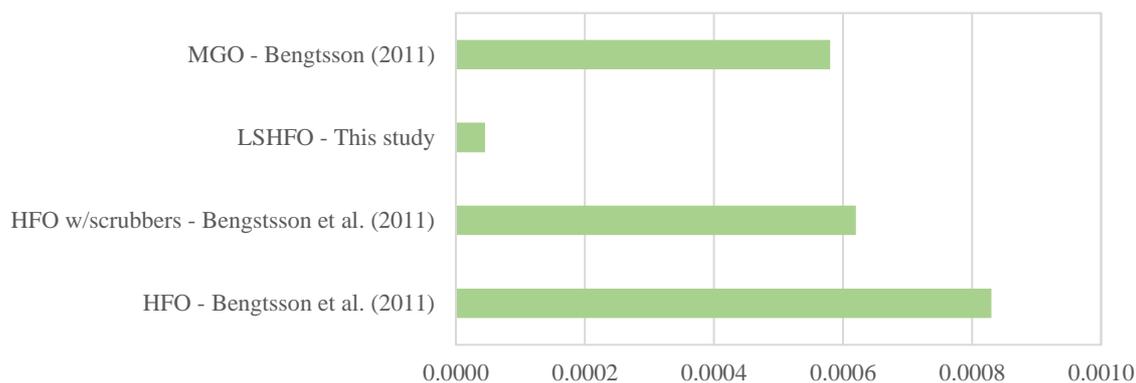


Figure 23: WTP life cycle impacts for TAP, in kg SO_{2e} per tkm

Considering the absolute contributions towards TAP, significant differences are observed. Differences in results are mainly due to key methodological choices as extensively discussed in Section 6.2.2.1. Nonetheless, the differences in results between HFO, HFO with scrubbers and MGO modeled after Bengtsson et al. (2011), are considered relevant and worthy of a further analysis.

The use of HFO with scrubbers over a life cycle perspective represent a decrease of approximately 25% of the impacts when compared to the use of HFO. On the other hand, the use of MGO leads to a decrease of 7% if used instead of HFO with scrubbers, making it the fuel with the best performance towards TAP, according to Bengtsson study results. However, it should be noted that the availability and price of MGO are a constraint, thus making the use of HFO with scrubbers a more feasible option despite the high price associated with its implementation. Notwithstanding, it should also be taken into account that the production, dismantling and further EOL of scrubbers were not considered in the study performed by Bengtsson et al. (2011), and that an increase of the total impacts might occur. Even though, in overall, results show that the use of HFO with scrubbers are a feasible option to decrease impacts towards TAP, and thus to decrease SO_x emissions from maritime transport.

6.3 Sensitivity analysis

The uncertainties associated with an LCA can essentially arise in every step of the study. The definition of system boundaries has already associated uncertainties, as processes

will be naturally cut-off, due to lack of data or due to scope and goal of the study. The same happens in the definition of functional unit, which needs to be in accordance with the goal of the study and should reflect the function of the product or system. If the functional unit does not comply with these requirements, the results will be not applicable for the specific product or service. Furthermore, when the system is modeled, the use of a background database introduces increased uncertainties as well, since the database can be based on weak or not up to date data, or even based on rough assumptions or extrapolation. Another uncertainty associated with the use of background databases is that most of the processes are based on European scenarios. Therefore, if processes based on global averages are used instead, the results might differ and might have associated higher uncertainties.

This section presents a sensitivity analysis to the parameters that were considered to have a significant uncertainty associated, and thus considered relevant to be further analyzed. The main uncertainties considered in this study rely on the HDS process, more specifically the consumption of electricity and hydrogen at the HDS unit, and on the energy and price partitioning coefficients. However, to assess the uncertainty associated with energy partitioning coefficients, changes would need to be made on fuel consumption specifications, at the operation phase, which is out of the goal of this study. Therefore, in Section 6.3.1 the uncertainty associated with the HDS process is assessed, and thereafter in Section 6.3.2, uncertainties associated with the price partitioning coefficients for HFO and LSHFO are analyzed. Noteworthy that the uncertainties associated with the PRELIM model are not considered in this section since they were already discussed in Abella et al. (2016b). Nonetheless, a further discussion with regards the assumptions made and the limitations of the model is provided in section 6.4.

6.3.1 Hydrodesulfurization process

In order to assess the uncertainties associated with the HDS process, two parameters were considered, electricity and hydrogen consumption. In this sense, to assess if significant changes occur towards the total impacts, an increase of 30% and 10% were applied to energy hydrogen requirements, respectively. Figure 24 presents a contribution analysis for GWP, in kg CO_{2e} per kg LSHFO. GWP was selected from the eighteen impact

categories since hydrogen and electricity production contributes greatly to the total impacts towards GWP, as shown in Section 5.4.

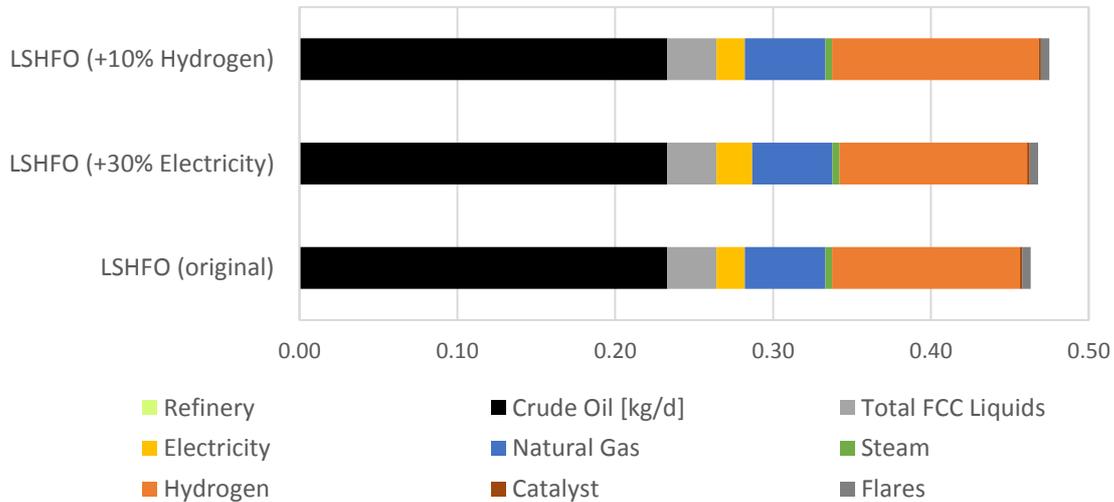


Figure 24: Differences in impacts for GWP, in kg CO₂ per kg LSHFO

Results show that small variations in hydrogen leads to higher impacts than variations in the electricity parameter. This is associated with the fact that the consumption of hydrogen is significantly higher.

6.3.2 Partitioning coefficients

Due to tightened regulations, an increase in demand of LSHFO is expected and a subsequent decrease in the demand of HFO, since the maritime sector will not be able to use this fuel in a short-term, except if used in combination with tailpipe technologies such as scrubbers, as presented in Section 6.2.2.2. However, due to production constraints at the refinery, LSHFO might not be available at the quantities required by the maritime industry, thus leading to the increase of its price. As in the modeled refinery scheme VR and Slurry oil are the streams that result into HFO and consequently LSHFO, changes in the prices of these streams were performed. A decrease of 10% was considered in the price of VR and a decrease of 5% in the price of slurry oil, thus reflecting a total decrease of 15% in HFO price. A bigger percentage of change was assigned to VR since it presents the higher fraction of HFO feed. Figure 25 presents the results for GWP by considering the referred price changes.

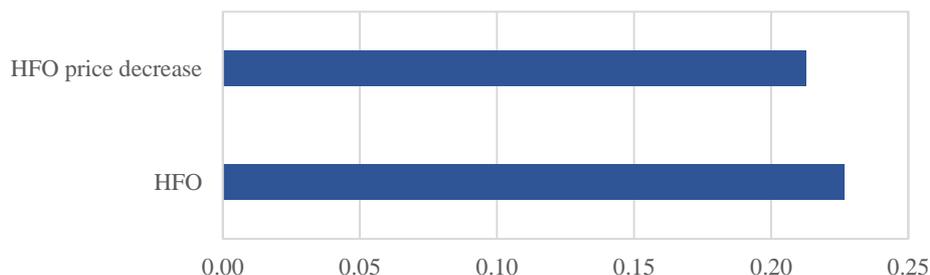


Figure 25: Differences in impacts for GWP, in kg CO₂ per kg HFO

As illustrated, a decrease in VR and slurry oil prices leads to a decrease of approximately 6% of the calculated GWP for HFO. Therefore, quite significant changes to the overall GWP can occur due to small changes in the market. It can therefore be argued that economic allocation is not the best model to allocate the impacts at the refinery due to its sensitivity to price fluctuations. As the price of refinery products might suffer significant changes due to production constraints or due to changes in demand, the use of economic allocation will lead to increased uncertainties in results, and will make comparison across studies describing impacts of fuel production more complicated as price information is often not readily available. In this sense, results show that energy allocation was the best option to allocate the impacts at the refinery from the allocation models considered in this study.

6.4 Opportunities for further research

It has been the aim of the study to develop a LCI of a generic refinery, including all flows and inflows of all relevant processes. However, due to lack of publicly available data and without the collaboration of an external partner with expertise in this field, this task was only possible through the use of PRELIM model. However, the use of the data provided by PRELIM has associated uncertainties and limitations.

One of the major limitations of PRELIM model is associated with the fact that it only modeled five main refinery products, namely, gasoline, jet fuel, ULSD, heating oil and HFO. However, a crude oil refinery can produce much more fuel products, such as liquefied petroleum gas (LPG), MGO and MDO, among others. Besides, PRELIM modeled ULSD instead of diesel as one of the main refinery products. Therefore, the

impacts associated with the production of diesel could not be quantified, neither the possible difference in impacts between the production of diesel and ULSD could be discussed. In addition, the model did not consider the desulfurization of HFO, and thus assumptions were made with this regard, leading to increased uncertainties as discussed in Section 6.3.1.

Another limitation associated with the referred model is that it assigns the emissions at a refinery level instead of a refining-process-level, as discussed in Section 4.1. In this sense, annually average emissions from U.S. refineries were used to quantify the emissions of the most relevant processes. This of course, imposes a significant level of uncertainty and thus constitutes a limitation for the study results. Besides, no-direct emissions other than GHGs were not considered due to lack of data, which also constitutes a study limitation that should be considered in a future research.

Still regarding PRELIM model, it is noteworthy to mention that a natural gas-fired power refinery was assumed instead of a coal-fired or low carbon power plant. Therefore, differences in results are expected to occur if the other types of power plants were used instead. However, as it was assumed that a generic refinery uses mostly natural gas as its main source of energy, the assessment of the impacts associated with the use of the other energy sources was considered out of the goal of this study. Nevertheless, in a further research it would be important to understand if a change in the main energy source at the refinery leads to a significant change in the total results. Moreover, it would be interesting to assess which energy source presents lower impacts per kg of fuel at the refinery gate.

Another opportunity for further research is associated with the modeling of HFO by considering the use of exhaust gas scrubbers during the operation phase. This would allow a further understanding of the potentiality associated with the use of such technology to decrease emissions when compared to LSHFO. In addition, the modeling of MGO and MDO at the refining process should be considered as well in a further research, thus contributing to the ongoing discussion about the potential of low-sulfur marine fuels to decrease emissions associated with maritime transport.

7 Conclusion

The goal of the study was to assess and compare the environmental impacts associated with the production of marine fuels with different sulfur contents over a life cycle perspective. Aiming to understand if a low-sulfur marine fuel is a promising solution to decrease the emissions of maritime sector. The selected marine fuels were HFO and LSHFO with a sulfur content of 3.5% and 0.1%, respectively.

According to literature findings, a shift from HFO towards low-sulfur marine fuels such as MGO and MDO leads to a decrease of acidification and eutrophication potentials. However, previous studies results differ in terms of impacts for GWP, when a shift towards a low-sulfur marine fuel occurs. Some studies state that a decrease of GWP occurs, whereas others state that it leads to an increase of impacts for GWP, which occurs during the refining phase, being partly offset during the operation phase. However, these studies did not perform a life cycle inventory of the refining process, but rather used background processes from well-known life cycle databases, neither considered vessel's construction and EOL. Besides, none of the considered studies assessed LSHFO. Considering these methodological differences and the main research questions of this study, the following conclusions were obtained.

The refining process presents a high contribution towards GWP and FDP. It also contributes significantly to HTP and TAP, but by a relative lower extent. The main contributor for the impacts associated with the refining process is crude oil extraction. However, for LSHFO hydrogen and electricity production also presents an important contribution, accounting in average for 16% and 7% of the total impacts, respectively. It was concluded that this is caused by the sulfur removal process, which leads to an increased consumption of hydrogen and electricity at the refinery in the order of 46% and 12%, respectively.

Additionally, it was concluded that the allocation models considered to allocate the emissions at the refinery presented some differences towards the total impacts. In general, mass-based allocation presented higher impacts than energy and price-based allocations. Furthermore, it was found out that HFO is the refinery product that presents higher

differences between the different allocation models considered, closely followed by LSHFO. HFO mass-based allocation presented 5% and 35% higher impacts towards GWP than energy and price-based allocation, respectively. On the other hand, LSHFO mass-based allocation presented 4% and 25% higher impacts than energy and price-based allocations.

From a life cycle perspective, crude oil extraction, ship construction and ship operation were found out to be the life cycle phases that contribute most to the total environmental impacts. Moreover, it was found out that the results between HFO and LSHFO differ in terms of refining and operation phases contribution. By analyzing the relative contribution of each phase towards GWP, ship operation decreases from 84.8% to 79.3% when a shift towards LSHFO is performed, while refinery operation increases from 1.7% to 5.7%.

Furthermore, it was concluded that a shift towards LSHFO presents trade-offs between the impact categories. GWP presents an increase of 2% when LSHFO is considered instead of HFO, whereas TAP and PMFP presents a decrease of 47% and 19%, respectively. The increase of 2% towards GWP occurs upstream, during the refining phase, due higher energy and hydrogen requirements to produce LSHFO.

Overall, it cannot be concluded that LSHFO is a promising solution to decrease maritime emissions since it leads to trade-offs between important impact categories. Moreover, its production cost and availability might present a constraint to maritime transport. Therefore, other solutions should be considered instead to decrease SO_x emissions. A solution that might avoid trade-offs between impact categories from a life cycle perspective and, at the same time, allows the decrease of SO_x emissions during the operation phase is the use of exhaust gas scrubbers. Therefore, this measure would allow maritime transport to comply with the tighten regulations enforced by IMO as well as the continuous use of the relative cheap HFO by this sector. Nonetheless, the production of such technology might lead to increased impacts upstream, and therefore, further research is required.

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Appendices

Digital Appendix A

This appendix provides supporting information, such as LCIs of refinery and bulk carrier, Arda files and associated results, and can be found at:

<https://www.dropbox.com/sh/jytb6nh2waxh5e5/AADt9gu2CesiVOlTO2fDLKBaa?dl=0>