The potential of drop-in biofuels for the maritime industry

A MILP optimization approach to explore future scenarios

SDPO.20.035.m.

D.F.A. van der Kroft

TU Delft

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by

D.F.A. van der Kroft

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TU Delft

Preface

This thesis is my final work to complete the Master's program Marine Engineering at the TU Delft. This research has been carried out in collaboration with GoodFuels, TNO, and Maritiem Kennis Centrum (MKC).

Firstly, I would like to express my gratitude to my supervisor Jeroen Pruyn. Performing nine months of research on your own can be challenging, and Jeroen provided me with excellent guidance. I was impressed with his quick responses and helpful comments that led to interesting discussions and insights. I would also like to thank Pieter 't Hart, Ruud Verbeek, Bart Hellings, Ayla Uslu, and Tom van den Beek for providing me with guidance and knowledge.

From a young age, I knew that I wanted to be an engineer, just like my grandfather. I regret that he cannot witness this moment with me anymore, but I am thankful that he provoked my curiosity in technology.
I enjoyed working on this study for the past nine months and I hope you will enjoy reading it!

D.F.A. van der Kroft
Amsterdam, November 2020

Executive summary

The shipping sector accounts for a significant share (±2.5%) of global Greenhouse Gas (GHG) emissions. Although the International Maritime Organisation (IMO) has introduced measures to decrease air pollution, global regulations that specifically target GHG emissions from shipping do not exist. Additionally, shipping is not included in the transport targets proposed by the European Union in their Renewable Energy Directive II (RED II). It seems contradictory that GHG emissions from shipping are not regulated, while these emissions are expected to experience a significant increase over time [124]. Nevertheless, the IMO has set ambitious goals to decrease GHG emissions from shipping by 50% in 2050 compared to 2008 levels.

In a study of Bouman et al. [30], several potential emission reduction measures for shipping were evaluated. This analysis showed that biofuels have a considerable potential to reduce GHG emissions emitted by ships. Biofuels are one of the few renewable fuels that are commercially available at this stage. Their drop-in character ensures that little to no adjustments are required to existing infrastructure. Additionally, biofuels contain negligible amounts of sulfur and can be blended gradually into the existing fuel mix.

However, there are also some uncertainties concerning the large-scale usage of biofuels. One significant barrier is the sustainable availability of suitable feedstocks. Currently, only biofuels made from oils and fats are commercially available. Most of these oily feedstocks contain vegetable oil. Due to the fuel versus food debate, using these edible feedstocks for the production of biofuel is a highly controversial topic. On top of that, some of these feedstocks impose a severe risk on Indirect Land Use Change (ILUC). In the nearby future, lignocellulosic and waste feedstocks might also become available for fuel production. Usage of these new biofuel technologies and feedstocks might open up opportunities to achieve the targets proposed by the IMO. However, the potential of these drop-in biofuels for the maritime industry is at this stage relatively uncertain. To address this potential, it is essential to analyze how future biofuel demand from the shipping sector aligns with the spatial availability of biomass feedstocks. Such an analysis could clarify the efforts and investments needed for compliance with the proposed GHG emission reduction targets. Additionally, it could help to draft new regulations that prescribe a share of renewable fuel. Consequently, the following research question is formulated.

"To what extent will drop-in biofuels be able to economically realize the intended local and global emission reductions for the shipping industry between 2020 and 2050?"

The objective of this study is to on the one hand look into the global availability of various biomass feedstocks and on the other hand look at the future demand for drop-in biofuels from the shipping industry. When both the supply of biomass feedstocks and the demand for marine drop-in biofuels are determined, a supply chain optimization can be performed to visualize future trade-flows, the most feasible locations of new bio-refineries, and all associated costs and emissions from Well-to-Tank (WtT). To capture the embedded uncertainties regarding the availability of biomass and the demand for biofuels, several scenarios are developed. The resulting trade-flows can be used to identify the main importers and exporters of biomass and biofuel. This will also give insight into the total costs and emissions during the life-cycle of the produced biofuels.

After a thorough literature review, it was decided to make use of Mixed Integer Linear Programming (MILP) to model the marine biofuel supply chain. Biofuel supply chains often consist of the same links. The feedstock is cultivated and harvested after which it is transported to a processing facility. When processed, the end product is delivered to the consumer. In the case of advanced biofuels, often an additional upgrading step is required. It is inefficient to transport low-density biomass over large distances. Therefore, it was decided to model the supply chain as a two-stage system. This entails the physical separation of the processing and upgrading facilities. To decrease the size of the studied topic, the scope of this study was narrowed. The spatial scope is set to global, dividing the world into 18 distinct areas. Each area contains at least one bunker hub. Additionally, five conversion technologies were selected, based on their drop-in character and potential application for the shipping industry. The selected fuels were Fatty-Acid Methyl Ester (FAME), Hydrotreated Vegetable Oil (HVO), Fast-Pyrolysis (FP), Hydrothermal Liquefaction (HTL), Gasification Fischer-Tropsch (GFT). Feedstocks were split-up into seven categories, oil crops, waste oils, agricultural residues, forestry residues, (lignocellulosic) energy crops, solid waste, and liquid waste.

After developing the MILP model, the regional supply of the in-scope biomass feedstocks was determined. For this purpose, a data-driven approach was used. To determine the amount of feedstock that might be available for the production of marine biofuels, other competing users were deducted. Three competing users were identified, transport without shipping, traditional heat, and renewable heat and power. It was observed from the literature that there exists a lot of uncertainty around the estimation of future biomass availability. To be on the safe side, it was chosen to use estimates from more conservative studies. The main takeaway from the biomass availability analysis was the limited availability of vegetable and waste oils for the production of biofuels. The production of vegetable oils is assumed to grow in accordance with the growth of food consumption, while the road and aviation sector are expected to gain an increasing demand for oil and fat-based biofuels. The availability of waste oils contains a measure of uncertainty, but its scalability turned out to be limited in all scenarios. Aviation and road are expected to create more value out of oils and fats compared to shipping and thus experience a competitive advantage. Therefore, these industries represent severe competition for the maritime industry. It was shown that the projected availability of oils and fats does not suffice for being on track with the IMO targets in each of the supply scenarios. In the Low Supply (LS) scenario, non of the proposed emission reduction targets could be met until 2025. In the High Supply (HS) scenario, compliance with the RED II targets until 2025, while only using oils and fat-based biofuels, was considered possible. This should raise awareness about the need for fast development and up-scaling of new technologies, which is required to reach these targets. Until advanced biofuel technologies become commercial, possible prescriptive blending requirements for shipping are in the order of 0.6%-6%, dependent on the spatial introduction of these regulations.

Next to the supply side, the future demand for marine biofuels is also uncertain. The main driver of the demand for marine biofuels is the existing regulatory framework. Because GHG emissions from shipping are at this stage not regulated, several demand scenarios were studied in which shipping should comply with targets from the RED II and the IMO. Three energy demand scenarios from the Third IMO GHG study were used in combination with three different spatial distributions of marine energy demand. The European scenario evaluated the possibility of Europe being the only region that will regulate GHG emissions from shipping. The Most-Likely (ML) scenario evaluated the case in which only front running countries would comply with set targets. The World scenario imposed the targets of the IMO on all studied ports.

Combining the developed optimization model, supply scenarios, and demand scenarios, a comprehensive scenario analysis was performed. This analysis showed that enormous investments into new bio-refineries are required to reach the targets proposed by the European Union (EU) and the IMO. Additionally, the average costs of biofuels were determined to be between 900-1200 EU/ton for an average emission reduction of 68-95% compared to Heavy Fuel Oil (HFO). From these emissions, around 80% can be assigned to the upgrading phase, which is a consequence of the required hydrogen. Emission reductions of 70-80% compared to HFO are determined to be realistic. When reaching for higher emission savings, the costs rise quickly. It was also identified that over time, firstly costs decrease due to economies of scale, but consequently go slightly up. Rising demand for biofuels induces the need for the usage of biomass that is more difficult to access and is therefore associated with higher costs and emissions.

Furthermore, the usage of a mix of feedstocks was observed to be most feasible. Agricultural residues were the preferred choice when looking at the entire period. Hydrothermal Liquefaction (HTL) was found to be the preferred choice of technology. This is mostly a result of the possibility to use a wide range of feedstocks and the modest amount of upgrading required for this fuel. The most feasible locations of new bio-refineries were found to be dependent on the spatial distribution of demand. For the European and ML scenario, the main refinery hubs were found to be Western Europe, Southern Europe, and Northern America. For the World scenario, the locations of bio-refineries were somewhat more distributed. However, the same refinery hubs were again identified, with the addition of Eastern Asia.

The resulting trade-flows can be split-up into the trade of the intermediate and the biofuel. The main exporting regions of the intermediate product (biomass suppliers) were found to be Southern Asia, Eastern Asia, Northern Europe, and Northern America. The main importers of the intermediate products were found to be Western Europe, Southern Europe, and Northern America for the Europe and ML scenarios. For the world scenario, Northern America and Western Europe were replaced by Western and Eastern Asia. In the Europe and ML scenario, Southern Europe was found to be the most feasible exporter of biofuel. In the World scenario, Western Europe and Northern America were added to the main biofuel exporting regions. Importers of biofuels were distributed in all studied scenarios.

Combining all findings, an answer to the proposed main research question can be formulated. With the use of drop-in biofuels, emission reductions of ± 80% compared to HFO can be achieved for around 900-

1200 EU/ton, dependent on the studied scenario. When lower fuel quality is accepted, less upgrading would be required, leading to a more affordable and sustainable fuel. Further research into (partly) skipping the upgrading phase is therefore encouraged. The limited availability of oils and fats was found to be the most significant barrier for the large-scale use of biofuels in the maritime industry. However, advanced biofuel technologies offer the opportunity to use a variety of other biomass feedstocks that are abundantly available. It can therefore be concluded that adequate policy mechanisms that, on the supply side, encourage the rapid development of new biofuel technologies, and, on the demand side, offer incentives that close the price gap with fossil fuels, are essential to expedite the transition to renewable fuels.

Contents

List of Figures

Acronyms

AIS Automatic Identification System. 47

ATJ Alcohol-to-Jet. 41

BC Base Case. 67

BD Base Demand. 82

CAPEX Capital Expenditures. 58

CCS Carbon Capture and Storage. 2

CHP Combined Heat & Power. 40

CRF Capital Recovery Factor. 58

ECAs Emission Control Areas. 3

ECTS Emission Cap and Trade System. 52

EIA U.S. Energy Information Administration. 41, 156

ETS Emissions Trading Scheme. 4

EU European Union. vi, 1, 3, 4, 17, 121

FAME Fatty-Acid Methyl Ester. v, 6, 7, 10, 35, 58, 60, 62, 64, 65, 69, 74, 76, 79, 86, 99, 104, 107, 115, 116, 121

FAO Food and Agriculture Organisation of the United Nations. 35–38, 41, 43, 128

FOB Free on Board. 55, 57

FP Fast-Pyrolysis. v, 36, 57, 69, 74, 86, 105, 116, 124

FT Fischer-Tropsch. 41, 57, 58, 61, 65, 70, 71, 77

GDP Gross Domestic Product. 7, 48

GFT Gasification Fischer-Tropsch. v, 36, 69, 105, 116

GHG Greenhouse Gas. v, vi, 1, 3–5, 7, 8, 17–19, 26, 47, 50, 52, 53, 59, 61, 62, 72, 74, 76, 77, 81, 86, 92, 96, 100, 104–106, 113–115, 119, 121, 124, 171

HEFA Hydrotreated Esters and Fatty Acids. 41

HFO Heavy Fuel Oil. vi, 72, 81, 87, 92, 100, 113, 121

HS High Supply. vi, xiii, 34, 79, 81, 91, 109

HTL Hydrothermal Liquefaction. v, vi, xv, 18, 36, 38, 41, 57, 58, 64, 65, 69, 71, 74, 77, 86, 91, 95, 104, 105, 107, 114, 116, 122, 124, 174

HVO Hydrotreated Vegetable Oil. v, 6, 7, 10, 35, 58, 62, 64, 65, 69, 70, 74, 76, 77, 79, 86, 91, 95, 99, 104, 107, 115, 116, 121

ICE Internal Combustion Engine. 1, 57

IEA International Energy Association. 40, 41, 47, 48, 143, 156

ILUC Indirect Land Use Change. v, 4, 35, 43, 61, 118, 119

IMO International Maritime Organisation. v, vi, 1, 3–5, 7, 17, 19, 47, 48, 52, 53, 72, 79, 81, 95, 119, 121

IPCC Intergovernmental Panel on Climate Change. 38

LCA Lifecycle Analysis. 17, 59–61

LCFS Low Carbon Fuel Requirement. 52

LHV Lower Heating Value. 64

LNG Liquefied Natural Gas. 95

LS Low Supply. vi, xiii, 33, 79, 81, 91, 96, 109

MARPOL The International Convention for the Prevention of Pollution from Ships. 3

MGO Marine Gas Oil. 116, 121

MILP Mixed Integer Linear Programming. v, vi, 14, 16, 20, 111, 119, 125

ML Most-Likely. vi, 79, 91, 109

MRV Monitoring Reporting and Verification. 4

MSW Municipal Solid Waste. 37, 38, 41, 64, 137, 138

NREAP National Renewable Energy Action Plans. 51

OECD Organisation for Economic Co-operation and Development. 41, 43

OPEC Organization of the Petroleum Exporting Countries. 7, 48

OPEX Operational Expenditures. 25, 57, 58

RCP Representive Concentration Pathways. 48, 171

RED Renewable Energy Directive. 4, 35, 118

RED II Renewable Energy Directive II. v, vi, 4, 36, 41, 50–52, 60, 81

RFS Renewable Fuel Standard. 52

RIN Renewavble Identification Number. 52

RJF Renewable Jet Fuel. 62, 77

RPR Residue-to-Product. 36

SEEMP Ship Energy Efficiency Management Plan. 4

SSP Shared Socioeconomic Pathways. 48, 172

TCI Total Capital Investment. 58

TPEC Total Purchased Equipment Costs. 58

UCO Used Cooking Oil. 6, 35, 36, 64, 118, 130, 131

UN United Nations. 3

WBA World Bioenergy Association. 32, 40

WtT Well-to-Tank. v

WtW Well-to-Wake. ix, xiv, 17, 19, 72

1
Introduction

The shipping sector is responsible for about 90% of international freight transport [2]. Emitting 2,5% of world-wide GHG emissions, the share in air pollution of the shipping sector is about the size of Germany [1, 10]. Although the relative emissions per unit of cargo transported are low compared to other transport modes, the total share in emissions of the shipping industry is significant [100, 105]. At this stage, the major part of the world shipping fleet still runs on fossil fuels. Besides the GHG emissions caused by the combustion of fossil fuels, also other factors like the finite oil supply, volatile oil prices, and the sustainability of the oil supply chain make the need for alternative propulsion solutions increase rapidly [135].

To comply with the recent implementation of International Maritime Organisation (IMO)'s new sulfur limit, shipowners need to either switch to alternative fuels or invest in scrubbers [57]. However, the installation of scrubbers has some downsides. Besides the high installation costs, usage of scrubbers increases fuel consumption. On top of this new global sulfur limit, multiple parties, including the IMO and the EU, have set targets for the reduction of GHG emissions, which are further discussed in section 1.3. In the third GHG study of the IMO, several scenarios indicated an expected increase of 50-250% in shipping related CO_2 emissions by 2050 [124]. This induces the need for solutions that can decrease these emissions.

Drop-in biofuels are biomass-based fuels that can be used in a conventional Internal Combustion Engine (ICE) engine without the need for modifications. Their implementation is a solution that can immediately be used by the shipping industry. Biofuels have a carbon-neutral cycle, meaning that the biofuel feedstocks absorb the same amount of CO_2 than they release in the air when burned. This causes the GHG impact of biofuels to be significantly less when compared to fossil fuels. The transition to biofuels can be performed gradually by starting with blending them into fossil fuels. In the automotive sector, already, a percentage of biofuel is blended with conventional fuels. For the shipping industry, the same could be done, but there is uncertainty about which feedstocks can cover the demand while minimizing GHG emissions from well to tank. To make sure that biofuel demand can be fulfilled while decreasing GHG emissions, an efficient biofuel supply chain is required [56]. Biomass is not evenly spread across the globe, which might cause regions to import or export large quantities of feedstock, possibly decreasing the emission reduction potential [64]. The goal of this thesis is, on the one hand, to determine the future marine biofuel demand in the most important shipping regions and, on the other hand, to determine the most feasible composition of the biofuel supply chain to fulfill this demand.

Firstly, this chapter contains some background information on biofuels in general and the regulatory framework regarding emissions in shipping. Chapter 2 contains the problem statement and also contains the subsequent research questions. In the consequent chapters, each (sub-) research question is answered separately. The thesis is finalized in chapters 10 and 11 which contain a discussion and a conclusion.

1.1. Principle of biofuels

The carbon emitted during the life-cycle of a fuel can either be carbon positive, neutral, or negative. Fossil fuels are carbon positive, absorbing fossil resources from the soil and expelling it as CO_2 into the air, creating net positive emissions. The use of biofuels can be seen as a carbon-neutral solution. The CO_2 that the feedstocks absorb during their lifetime to grow returns to the atmosphere when the biomass is converted into energy [134]. For accounting purposes, the Tank-to-Wheel (TtW) emissions of biofuels are considered to be zero. Carbon cycles can even be made carbon negative if they release less carbon in the air than they absorb when growing. A way to create a negative carbon cycle is by using Carbon Capture and Storage (CCS), capturing emissions and storing it undergrounds [98]. Usage of CCS is outside the scope of this thesis. In theory, biofuels are carbon-neutral, but in practice, the transport and conversion processes create additional emissions.

1.2. Biofuel pathways

There are various types of biofuels, which can all be produced from different feedstocks, using various conversion processes. An overview of these conversion pathways is shown in figure 1.1. Feedstocks are in this case divided into different categories. Usually, pre-treatment is performed to prepare the feedstock for processing. Pre-treatment includes processes like drying and milling of the feedstock. Consequently, a processing step is performed to convert the biomass into an intermediate bio-energy carrier. This intermediate product can then be processed again to convert it into a biofuel.

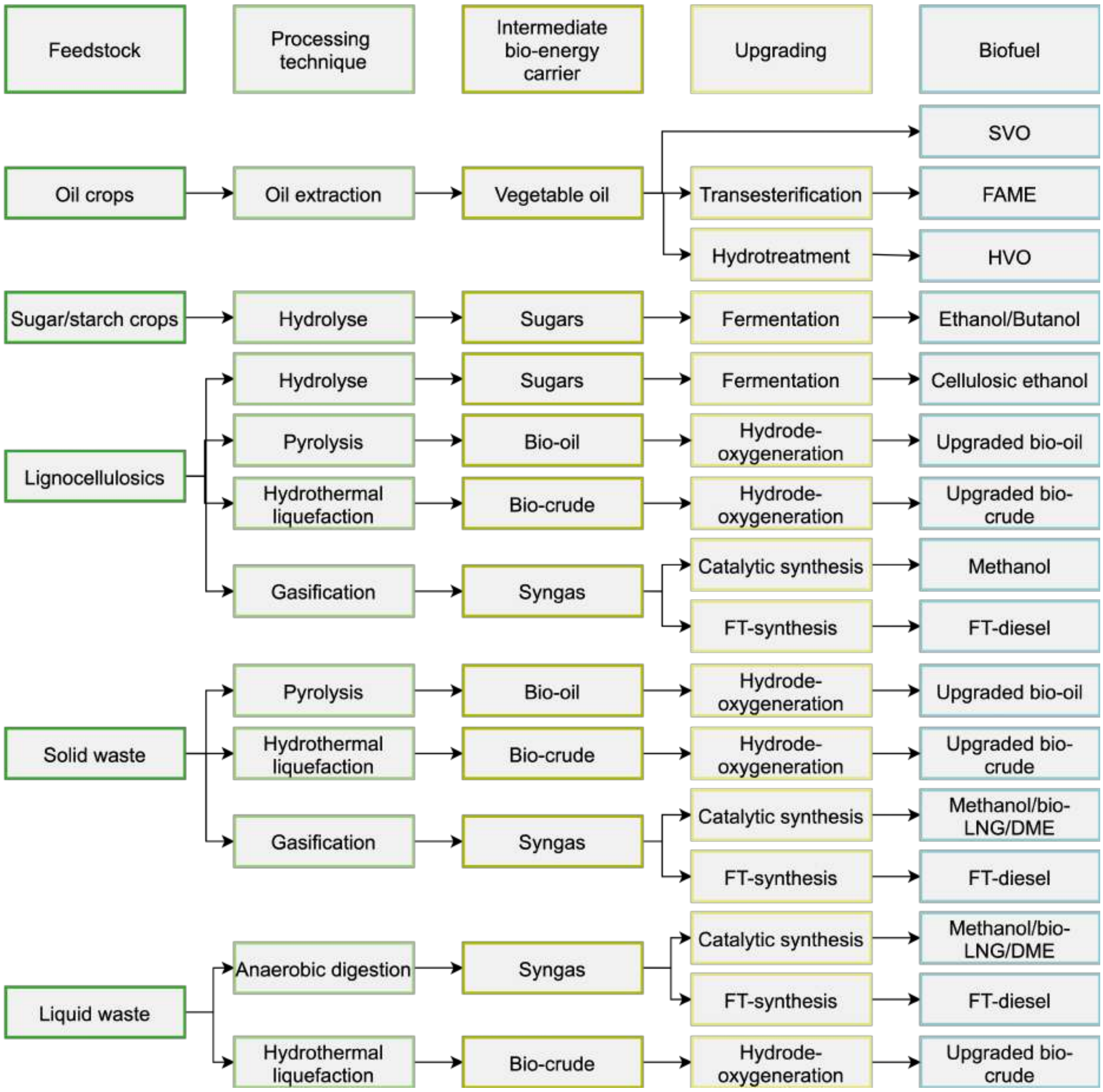

Figure 1.1: Various biomass-to-biofuel pathways.

1.3. Regulatory framework regarding emissions in shipping

To stimulate the deceleration of global warming, organizations and governments implement increasingly strict rules and regulations concerning emissions. Because shipping is a worldwide business and is not restricted to one location, it is difficult to make binding regulations on a regional level. Therefore, a lot of the measures taken serve more as targets or guidelines rather than regulations. The following paragraphs will elaborate on the implemented rules and regulations that have an impact on the usage of biofuels.

There are different organizations involved in regulating the shipping industry. The IMO and the EU have implemented regulations and targets regarding air pollution ([27]). Targets and regulations implemented by both organizations are discussed below.

1.3.1. International regulations

The IMO is a separate body of the United Nations (UN) and regulates the shipping sector on an international level [70]. Regulating the shipping sector reaches further than only air pollution, and therefore only part of the rules and regulations serve as emissions reduction drivers. According to the third IMO GHG study, GHG emission from shipping are expected to increase significantly in the coming decades, as shown in figure 1.2. As a response to this, the IMO introduced a provision in Annex VI of The International Convention for the Prevention of Pollution from Ships (MARPOL), representing the international policy for reducing GHG emissions and air pollution. The measures taken by the IMO can be categorized in short, medium and long term solutions and are summarized in table 1.1 ([139], [3]). Besides the GHG emission reduction strategy, the IMO recently implemented a global sulfur limit and also regulates NOx emissions. Emission Control Areas (ECAs)'s are implemented, representing coastal areas in which stricter emission regulations are applicable.

Although the IMO regulates sulfur and NOx emissions, GHG emissions are at this stage not regulated. Only targets for the reduction of these emissions, shown in figure 1.2, exist.

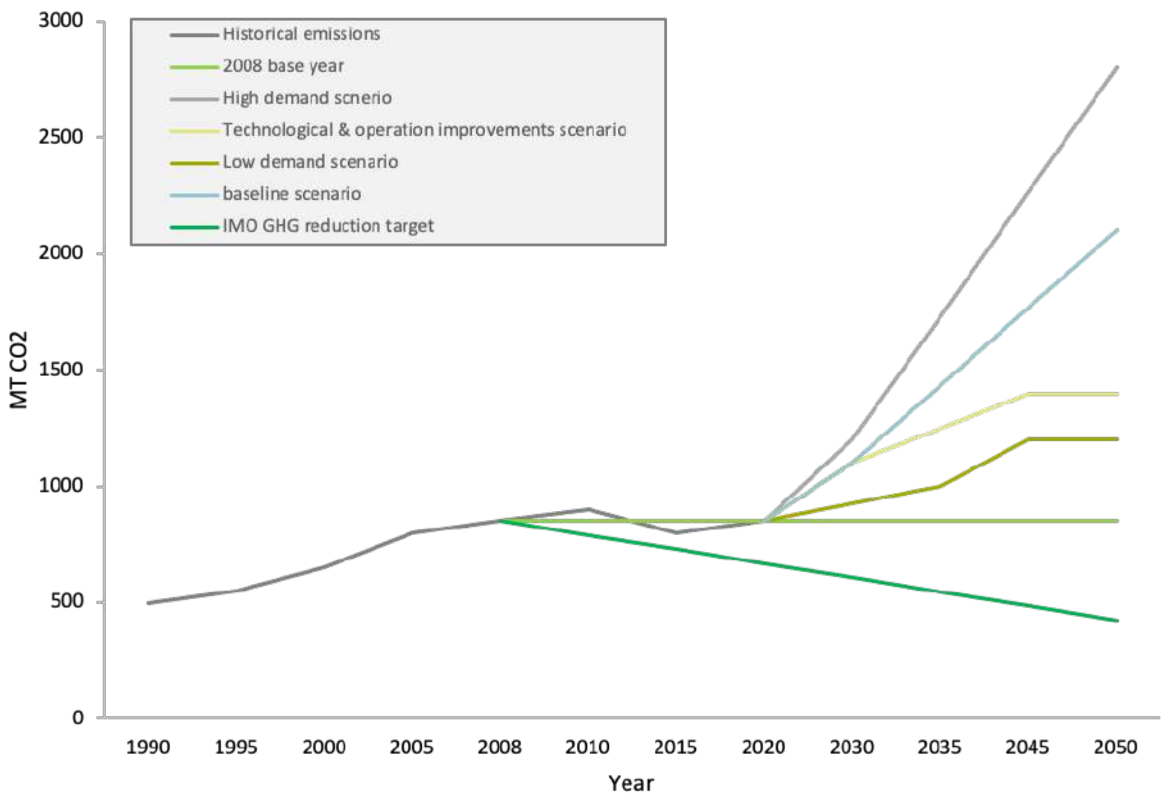

Figure 1.2: Forecast on CO2 emissions by shipping [124].

Table 1.1: GHG reduction strategy of the IMO [139].

Type	Years	Measure	Target
Short-term	2018-2023	New Energy Efficiency Design Index (EEDI) phases	New vessels
		Operational efficiency measures (e.g. SEEMP, operational efficiency standard)	In-service vessels
		Existing fleet improvement program	In-service vessels
		Speed reduction	In-service vessels
		Measures to adress methane and VOC emissions	Engines and fugitive emissions
Mid-Term	2023-2030	Alternative low-carbon and zero-carbon fuels implementation program	In-service vessels/Fuels/ New vessels
		Further operational efficiency measures (e.g. SEEMP, operational efficiency standard)	In-service vessels
		Market-based Measures (MBMs)	In-service vessels/Fuels
Long-term	2030 +	Development and provision of zero-carbon or fossil-free fuels	In-service vessels/Fuels/ New vessels

1.3.2. European regulations

EU regulations could greatly influence the deployment of biofuels in shipping. Despite the recognition of the fact that GHG emissions from shipping need to be addressed to comply with international targets like the Paris Agreement, there is no policy or target to reduce them at EU level [55]. The EU has some general emissions reduction targets, but shipping is not included.

Although there are no GHG emission targets for shipping yet, the EU has set some targets for the usage of renewable fuels in transport. These targets are set in the RED II, which is a revision of the Renewable Energy Directive (RED). The sub-target for renewable energy consumption in transport is set to 14% by 2030. This revision also raised the overall renewable energy resources consumption target for 2030 from 27% to 32% [5].

On top of these new targets, RED II also stated sustainability criteria for biofuels to count towards the 14% target. One of the difficulties of biofuels is that the feedstocks may compete with other industries like the food industry. Another problem is Indirect Land Use Change (ILUC). When cropland is used as a biofuel feedstock, it results in the shift of agricultural land to non-cropland. This can lead to deforestation and the unwanted release of CO_2, which is collected in the trees and soil. To prevent this from happening, RED II has implemented a limit to biofuels with high risk on ILUC.

Next to the limit on biofuels made from feedstocks that contribute to ILUC, also attention is given to so-called advanced biofuels. To stimulate the usage of certain feedstocks, multipliers are given when feedstocks are used that the EU believes are more sustainable than the ones currently used. These feedstocks are highlighted in RED II annex IX-A, and biofuels made from these feedstocks are defined as advanced biofuels by the EU. These biofuels are given a multiplier of two, meaning that the energy share obtained from the fuel may be counted double (virtually) for the target of 14%.

The general targets of the EU are enforced by a Emissions Trading Scheme (ETS), also called cap and trade [9]. This implies that the EU sets a cap on emissions and provides the possibility for organizations to buy allowance for emitting CO_2. By reducing the overall cap over time, total emissions are reduced.

In 2013, the EU started to involve shipping into the emission reduction targets. They set up a three-phase approach to do this [9, 55, 70]:

1. Implementing a system for Monitoring Reporting and Verification (MRV) of emissions
2. Definition of reduction targets for the maritime sector
3. Application of a market-based measure

The first part of this approach is monitoring and reporting of CO_2 emissions, from which the 2018 results are now available. This approach is similar to the approach of the IMO, which uses Ship Energy Efficiency Management Plan (SEEMP) to monitor emissions from ships. The next step is to formulate emission reduction targets for the shipping industry.

2
Problem statement

The previous chapter provided context to the subject of marine biofuels. This chapter aims to address the uncertainties that serve as an inducement for performing this study. The indicated uncertainties consequently lead to a set of (sub-)research questions.

2.1. Potential of biofuels for the shipping industry

Like discussed in section 1.3, the IMO set targets to reduce GHG emissions caused by shipping with 30% and 50% in 2030 and 2050, respectively. Many solutions are proposed in the literature to reach these targets. In the long term strategy of the IMO several emission reduction measures are integrated. Besides improving the technical and operational efficiency of the world fleet, alternative fuels play an important role in the decarbonization of the maritime sector. In research of Bouman et al. [30], several emission reduction options were evaluated, and biofuels were indicated as the measure with the highest emission reduction potential.

As stated before, a significant advantage of drop-in biofuels is the possibility to use them in a diesel engine without the need for modification of the storage facilities, engine, or the vessel itself. Partly because of this drop-in character, the global market for biofuels is growing and also affecting the shipping industry. In 2019, about 2% of all fuel oil sales in the Port of Rotterdam were biofuels [13].

However, there is some controversy about the sustainability of certain biofuels. Additionally, there is uncertainty about the emergence of new conversion techniques, the global availability of feedstocks, and the emissions reduction potential of drop-in biofuels. The large-scale implementation of drop-in biofuels for the shipping industry would require significant investments in new refineries, while it is unknown whether such investments will pay off in the long run. With the IMO targets in mind, it would be helpful to create insight into what the contribution of drop-in biofuels for the shipping industry could be. This leads to the main research question of this thesis:

"To what extent will drop-in biofuels be able to economically realize the intended local and global emission reductions for the shipping industry between 2025 and 2050?"

To clarify the uncertainties that are related to this research question, the next (sub) sections break down this problem into smaller pieces. This leads to the drafting of several sub-research questions.

2.2. The marine biofuel supply chain

In section 1.1, it was explained how biofuels reduce emissions according to the principle of a short carbon cycle. In essence, the tank to wake emissions of biofuels are considered to be zero due to this carbon-neutral principle. Nevertheless, during the well to tank phase of the biofuel supply chain, emissions are added to the life-cycle of the fuel. In other words, the more efficient the supply chain is in terms of minimizing costs and emissions, the more use of biofuels can contribute to decarbonizing the shipping industry. Optimizing this supply chain would contribute to the reduction of emissions caused by the shipping industry. To optimize the marine biofuel supply chain, it should be investigated how it could be modeled. This uncertainty leads to the first (sub-)research question of this thesis:

"How are biofuel supply chains previously studied and modeled?"

When it is known how the marine biofuel supply chain should be modeled, the input and parameters required to run the model should be acquired. This leads to the second (sub-) research question.

What are the economic, environmental and technological parameters that are required for the strategic supply chain optimization?

The supply chain of biofuels globally consists out of three main parts; collection and storage of the feedstock, conversion to biofuel, and transportation. In the following subsections, feedstocks for biofuel production and the conversion processes are further discussed.

2.2.1. Feedstocks for the production of biofuels

The sustainability of the feedstock has a significant impact on the emission reduction potential of the biofuel. Currently, the most widely available biofuels are bio-diesel (Fatty-Acid Methyl Ester (FAME), Hydrotreated Vegetable Oil (HVO)) and bio-ethanol. In figure 2.1 the distribution of feedstocks used for bio-diesel production is shown.

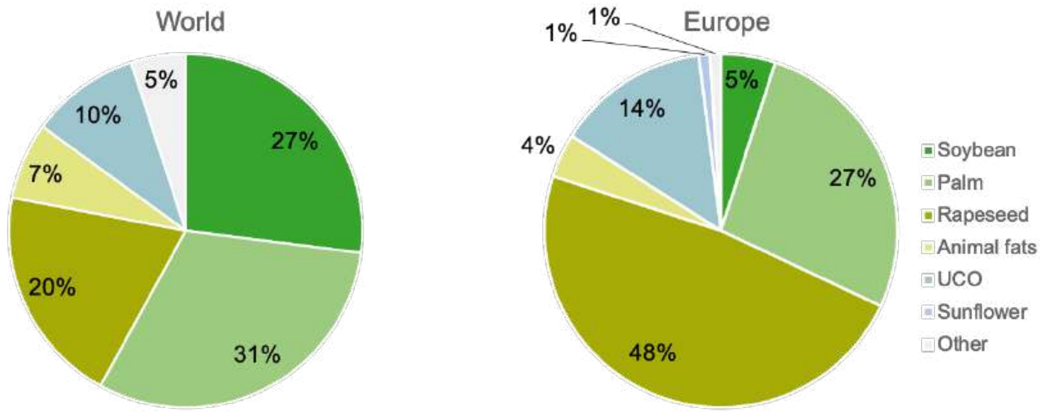

Figure 2.1: Feedstock use for the production of biodiesel [130].

At this stage, most biodiesel is made from edible oil crops. Vegetable oils are seen as a controversial feedstock because they are also used in the food industry, and there is limited supply [14, 26].

It should be noticed that most biodiesel is produced from palm, rapeseed, soybean, and Used Cooking Oil (UCO). UCO is a waste feedstock which is more convenient from a sustainability perspective. A disadvantage of UCO is that there is a limited available supply, and it is sensitive for fraud. For bio-ethanol, similar sustainability concerns about the feedstock exist.

Concluding from the above-mentioned problems regarding current biofuel feedstocks, there is a need for other biomass feedstocks that are widely available and do not cause sustainability issues. Much research is going on into the conversion of so-called advanced feedstocks to biofuels.

It is at this stage uncertain where these feedstocks are located. On top of that, it is uncertain what portion of these feedstocks would be available for the production of marine biofuels. Other industries might also be interested in the use of these feedstocks. This should be considered when estimating the availability. Therefore, research into the subject of feedstock availability for the production of marine biofuels would help to clarify the potential of biofuels for the maritime industry. This leads to the following sub-research question:

"Where are the in-scope feedstocks located and what quantity is there available for the production of marine biofuel?"

2.2.2. Conversion of feedstock to biofuel

The second part of the biofuel supply chain is the conversion of the feedstock. At this stage, several conversion techniques can be seen as technologically mature. Production of FAME is performed by (trans-) esterification of the fats inside the oil crops. For the production of HVO, oil crops undergo a hydro-treatment process, in which the aim is to remove as much oxygen out of the fuel as possible. Removing the oxygen increases the energy density and stability of the fuel, resulting in higher quality, but also more expensive fuel than FAME.

As earlier discussed, both FAME and HVO have their downsides for serving as a marine fuel. The major downside is the limited availability and sustainability concerns of the used feedstocks. Additionally, these fuels are still unable to compete with the low prices of fossil alternatives. Therefore, much research is performed at this stage to develop new biomass to biofuel pathways based on lignocellulosic and waste feedstocks.

Although there is much research going on in the development of these techniques, it is uncertain when they will be commercially available. It is also uncertain how fast the refinery capacity will grow to produce these fuels on a large-scale. It is unknown what strategic future locations for these new bio-refineries would be.

Refineries could either be located near to the feedstock source or near to the demand site. This would impose the choice to either transport the feedstock, an intermediate product or the fuel itself. The following sub-research question can be stated based on the mentioned uncertainties:

"What are the most feasible future bio-refinery locations and what is the required regional capacity?"

2.3. Marine biofuel demand

To optimize the marine biofuel supply chain, the future demand for these fuels has to be studied. Besides estimating future bunker volumes, also the location of this demand needs to be specified. Global bunker demand is, in essence, relatively easy to locate, seeing that the 20 largest bunkering hubs are responsible for about 80% of bunker demand [6]. However, regional regulatory drivers might change the spatial structure of bunker demand.

A basis for estimating future marine biofuel demand would be to indicate the drivers for this fuel consumption. The main driver for bunker consumption is a combination of three factors, growth in international seaborne trade, marine transport efficiency improvements, and fuel substitution [110]. Global Gross Domestic Product (GDP) is related to the development of international seaborne trade, which is directly connected to shipping. In the World Oil Outlook of Organization of the Petroleum Exporting Countries (OPEC), global GDP is expected to increase with 3,3% per year in the coming 20 years, indirectly causing international seaborne trade to increase at a similar pace.

However, bunker demand is not necessarily expected to follow the same trend. The shipping industry takes measures to reduce fuel consumption in the coming decades. The IMO aims to make the existing fleet and newbuilds 25% more efficient in 2025 compared to 2014 levels [110]. Besides increasing the efficiency of the world fleet, also improving operational efficiency is expected to have an impact on fuel consumption. Also, measures like slow-steaming could decrease fuel consumption.

A driver that is mainly related to the demand for marine biofuels is the future regulatory framework. To decelerate global warming, the development of a regulatory framework concerning emissions is essential. Future regulations will force shipowners to decrease their emissions, which possibly increases the demand for alternative fuels.

On the other hand, ship operators are unlikely to switch to an alternative fuel until it is cost-effective, readily available, and compatible with existing or future infrastructure [138]. Due to the uncertainty about the content of the future fuel mix of the shipping sector, shipowners are reluctant to make adaptations to their fleet. This could increase the potential of drop-in biofuels seeing that they can be used without any modifications to the ship or engine, lowering the threshold for adoption of biofuels [78]. Hence, the only barrier for shipowners to switch to biofuels is the price gap with fossil fuels. Introduction of IMO's new sulfur limit might decrease the price gap between biofuels and low sulfur fossil alternatives.

Especially for the shipping industry, it is challenging to implement such a regulatory framework. Shipping is an international industry and thus hard to regulate on a regional level. Many studies agree on the fact that these difficulties could be overcome by implementing global market-based regulations [104]. This already happened in the form of the global sulfur limit, which caused ship operators to switch to low sulfur fuels or install scrubbers. This regulation had an immediate impact on the price spread between low and high sulfur fuel oil.

At this stage, there are no regulations on GHG emissions in shipping. However, the implementation of such global regulations seems unavoidable. A mandatory blending of biofuels is already applied to the road sector. It is not unthinkable that such measures will also be implemented in shipping. Like mentioned earlier, such regulations should preferably be implemented on a global level. If such regulations were implemented on a regional level, shipowners would decide to bunker elsewhere, nullifying the intentions and disturbing a level playing field. Another approach, in which ports do not allow ships to enter unless their tanks are filled with a certain percentage of biofuel, could partly solve the level playing field problem.

It would be interesting to look at the impact of global regulations regarding GHG emissions and admixture obligations. What blend percentage would be achievable, and what would be the potential GHG emission savings caused by such a mandate? The uncertainties concerning earlier discussed regional bunker demand and future regulations lead to the following sub research question:

"What will be the impact of different future regulatory scenarios on marine biofuel demand?"

2.4. Research questions

From the uncertainties mentioned in the previous section, the main research question that will be answered during this thesis is stated as follows.
Main Research Question

"To what extent will drop-in biofuels be able to economically realize the intended local and global emission reductions for the shipping industry between 2025 and 2050?"

To answer the main research question, the following (sub-) research questions split the problem up into smaller pieces.
Sub-Research Questions

i ***How are biofuel supply chains previously studied and modeled?***

ii ***Where are the in-scope feedstocks located and how much is there available for the production of marine biofuel?***

iii ***What will be the impact of different future regulatory scenarios on marine biofuel demand?***

iv ***What are the economic, environmental and technological parameters that are required for the strategic supply chain optimization?***

v ***What are the most feasible future bio-refinery locations and what is the required regional capacity?***

2.5. Methodology

To answer the previously mentioned (sub-) research questions, the methodology shown in figure 2.2 will be used.

The main steps of the methodology used in this thesis are:

1. Determine how to model the marine biofuel supply chain.
2. Model the marine biofuel supply chain.
3. Determine the availability of feedstocks.
4. Determine the future demand for marine biofuel.
5. Determine the technological, economical and environmental parameters for the model.
6. Verify and validate the model.
7. Run various scenarios.
8. Analyze the results.

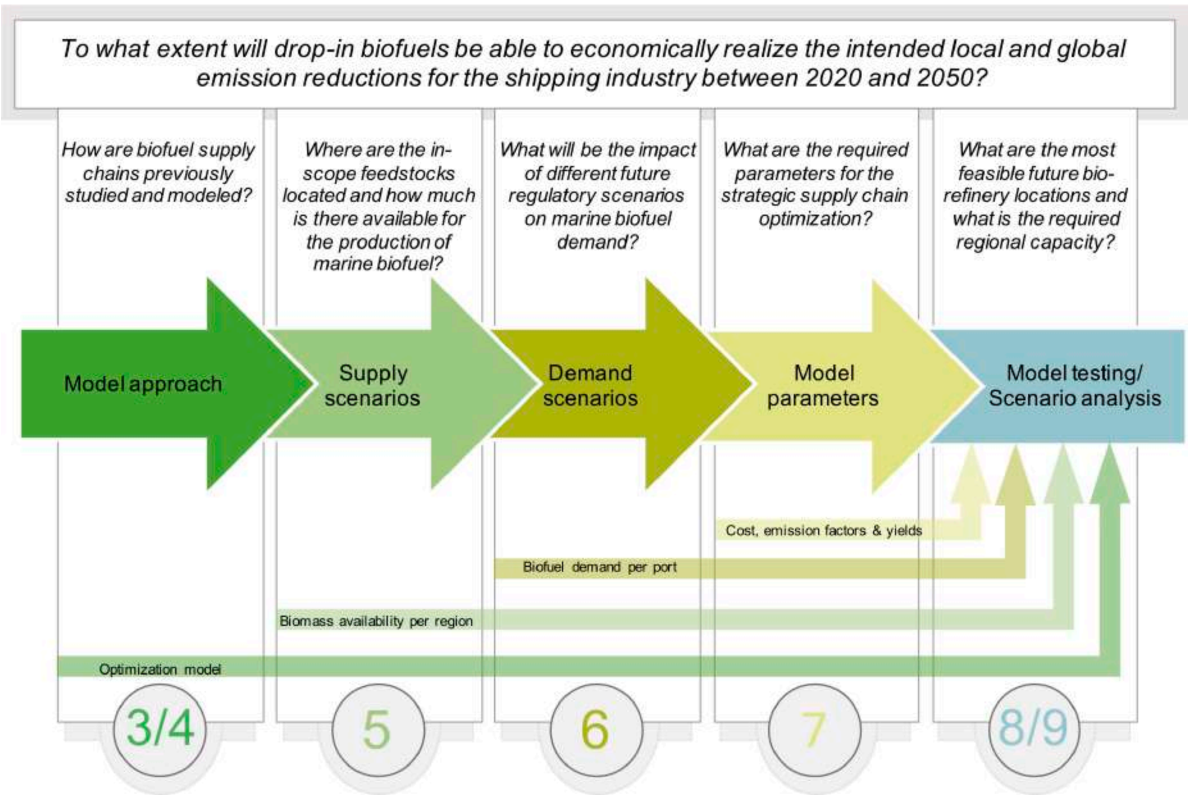

Figure 2.2: Methodology used in this thesis.

2.6. Scope

Looking into the optimization of the global marine biofuel supply chain is a fairly large task. Therefore, the scope of this thesis is limited to certain conversion pathways, feedstocks and regions.

2.6.1. Pathways

As indicated in section 1.2, there are many biomass-to-biofuel pathways. The focus of this thesis is on drop-in biofuels. Therefore, the scope is narrowed to the pathways shown in figure 2.3.

FAME and HVO are seen as bridging fuels. Until the other three pathways become commercial, FAME and HVO are the only biofuels available to bridge this gap. Analogous to fossil products, refining of the intermediate bio-energy carriers leads to multiple fuel fractions. Lighter fractions would be more suitable for higher value applications like the aviation industry. The more heavy fractions could be more suitable for heavy duty marine engines. However, no distinct fraction for marine usage is considered in this thesis. All fractions are lumped together, seeing that every fraction would be suitable for use in a marine diesel engine.

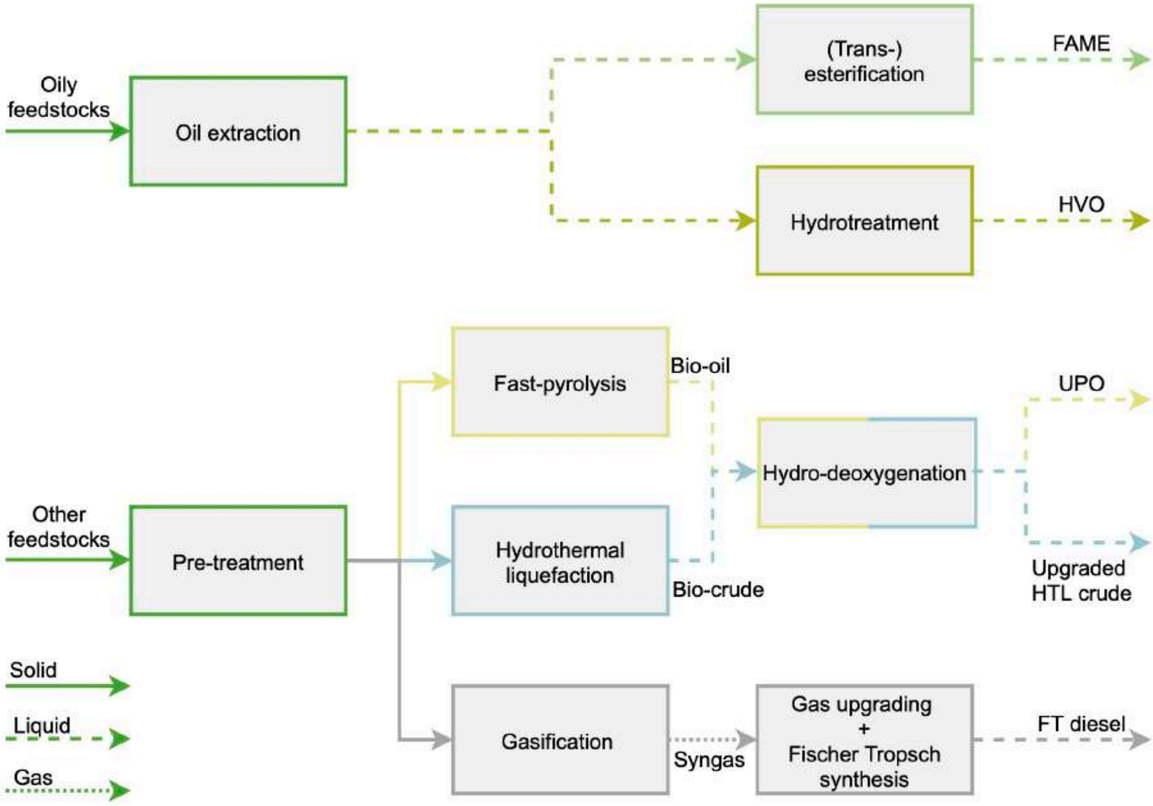

Figure 2.3: Pathways in the scope of this thesis. Partly adapted from Tanzer [126].

2.6.2. Feedstocks

The feedstock categorization used in this thesis is visualized in table 2.1.

Table 2.1: Feedstock categorization used in this thesis. Partly adapted from de Jong et al. [43].

Feedstock category	Feedstocks
Vegetable oils	Palm, sunflower, soybean and rapeseed
Waste oils	UCO and tallow
Agricultural residues	Grain residues
Forestry residues	Primary: Leftover from logging operations, early thinning or final felling (branches, stumps, tree tops, bark, sawdust etc.) Secondary: by-products and co-products of industrial wood-processing operation (bark, sawmill slabs, sawdust, wood chips etc.
Energy crops	Miscanthus, willow, poplar
Solid waste	Municipal solid waste
Liquid waste	Animal manure and wastewater sludge

2.6.3. Regions

In this thesis, the world is divided into 18 areas, indicated in figure 2.4. Each region contains at least one port, which serves as a node in the constructed network. It should be noticed that Eastern Europe reaches across the entire map, while having only one export/import node in St. Petersburg. The influence of this assumption on the results will be assessed afterwards.

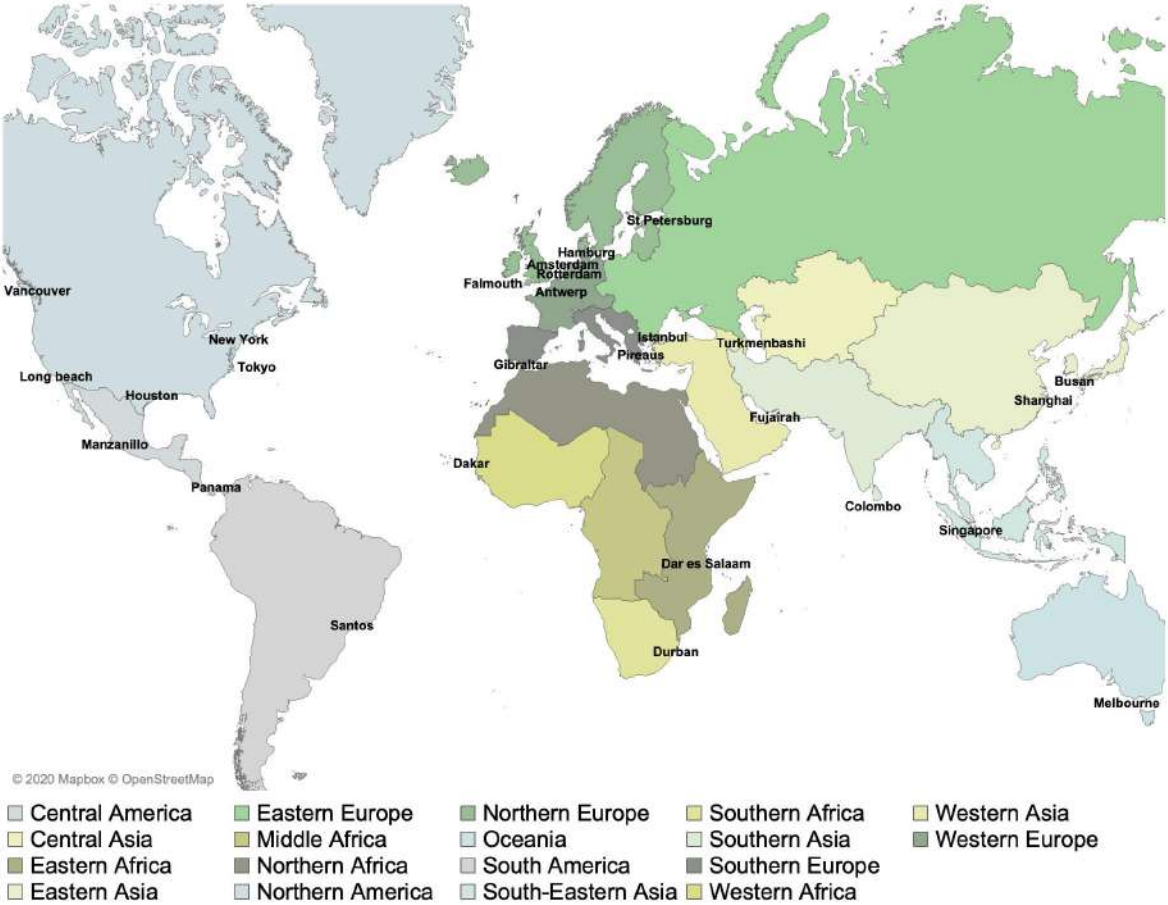

Figure 2.4: Regions and associated ports used in this thesis.

3

Literature review

This chapter aims to cover literature concerning the optimization of biofuel supply chains. First, different levels of supply chain modeling are discussed. Secondly, the consideration regarding different structures of supply chains is elaborated on. Lastly, it is indicated how others modeled biofuel supply chains and how this can be applied to the modeling of the marine biofuel supply chain. The goal of this chapter is to answer the first sub research question:

"How are biofuel supply chains previously studied and modeled?"

3.1. Structure of biofuel supply chains

In all reviewed studies, it was indicated that the biofuel supply chain consists out of the same stages, shown in figure 3.1. The process starts with a feedstock that is suited to be processed into a biofuel. The biomass product is then transported to a gathering point, which is usually nearby. It can be uneconomical to transport low-density biomass feedstock for long distances [7]. Biomass is often compressed into briquettes, bales, or pellets to make long-distance transport more efficient. Subsequently, the biomass is transported to a conversion plant where the biomass is processed into fuel. Finally, the biofuel is transported to the user. Although most biofuel supply chains are fundamentally similar, there are some variations in the distribution and processing strategies. These strategies involve the choice between centralized, distributed, or two-stage supply chains. In the case of petroleum refineries, economies of scale play an important role, and large centralized plants are mostly preferred. However, this is not necessarily the case for biofuels because it is not always evident that economies of scale outweigh the need for long-distance transport of low energy-dense biomass [142]. Therefore, a more distributed supply chain might be more suitable for biofuel production. Another

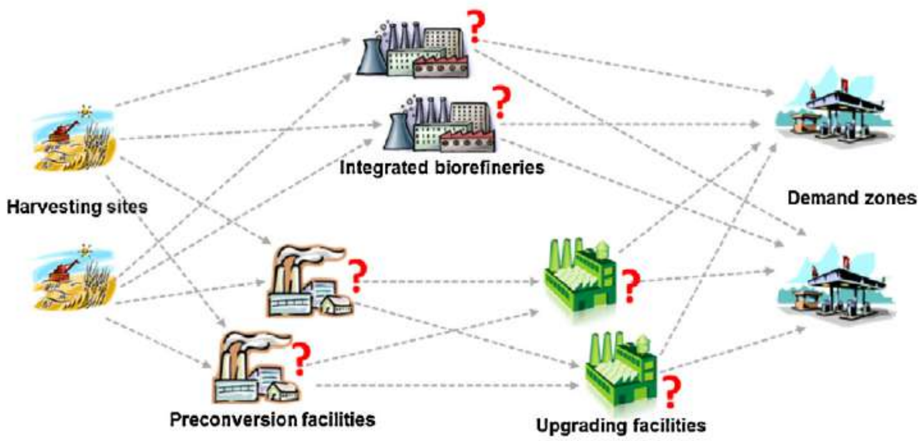

Figure 3.1: Different possibilities for biofuel supply chains [142].

type of strategy is a two-stage supply chain in which the biomass is first pretreated/processed at a nearby processing facility and then further upgraded into biofuel at a central refinery. The configurations discussed above are shown in figure 3.1. In this figure, different variations of harvesting sites, integrated bio-refineries, pre-conversion facilities, upgrading facilities, and demand zones are shown.

In a study of [42], several of these supply chain configurations were modeled to determine which was optimal for the production of bio-jet fuel. In a case study regarding biofuel production from lignocellulosic material in Sweden, they applied distributed supply chains when biomass became increasingly dispersed, but only saw a small cost-benefit (<1%) [42]. Sharifzadeh et al. [119] performed a similar case study in which they used an MILP model to choose between a distributed or centralized biofuel supply chain in the United Kingdom. They indicated that a centralized supply chain would suffice under deterministic conditions [119]. Studies that examined the trade-off between distributed and centralized supply chains concluded minor differences in costs. For this research, only centralized refineries are considered. The spatial scale of the studied area is international, and therefore it would be too intensive to study costs for inland transportation between pre-conversion facilities and upgrading facilities in detail. Because of the broad global scope of this supply chain optimization, two-stage refineries are a logical choice. With this, the intermediate product could be shipped and upgraded at an upgrading facility near the demand port. This induces the possibility of transporting a more energy-dense intermediate bio-energy carrier by ship, while also receiving the economic benefits of larger centralized bio-refineries.

3.2. Different levels of biofuel supply chain modeling

Yue et al. [142] made an extensive overview of key issues, challenges, and opportunities concerning the optimization of biofuel supply chains. Four levels of modeling are described by Yue et al. [142], molecule, process, supply chain, and ecosystem. In figure 3.2, these system layers are shown.

All mentioned scales are interconnected. To get a holistic view of the entire biomass to the bio-energy system, a multi-scale model and optimization framework is required [142]. A combination of multiple studies, evaluating different system layers eventually leads to better performance of the entire system. Within the four different layers, various levels of spatial and temporal scales can be investigated.

On the ecosystem level, the whole system is studied on impact and footprint. When studying both the environmental and economic performance of the system, multi-objective optimization can be used. Seeing that optimization of two variables can lead to conflicting objectives, Pareto-optimal solutions can be obtained to reveal the trade-offs [142].

On the supply chain level, optimization tools play an essential role in creating the optimal network configuration. Such a network often consists of multiple sites and echelons, requiring coordination across the entire supply chain network [142]. At this level, also optimal locations of infrastructure, like refineries, can be determined. The marine biofuel supply chain level can be reviewed on different spatial scales, ranging from regional to national to international. The higher the spatial level, the less detailed the supply chain is studied.

On the process level, the processes and units within the biomass to biofuel conversion refineries are studied. This process level often consists of techno-economic assessments of the various pathways.

On the molecule level, theoretical and experimental research into reaction pathways can serve as a building block for the lower-level systems. In other words, lower-level systems provide data serves as input for more detailed modeling of the higher systems.

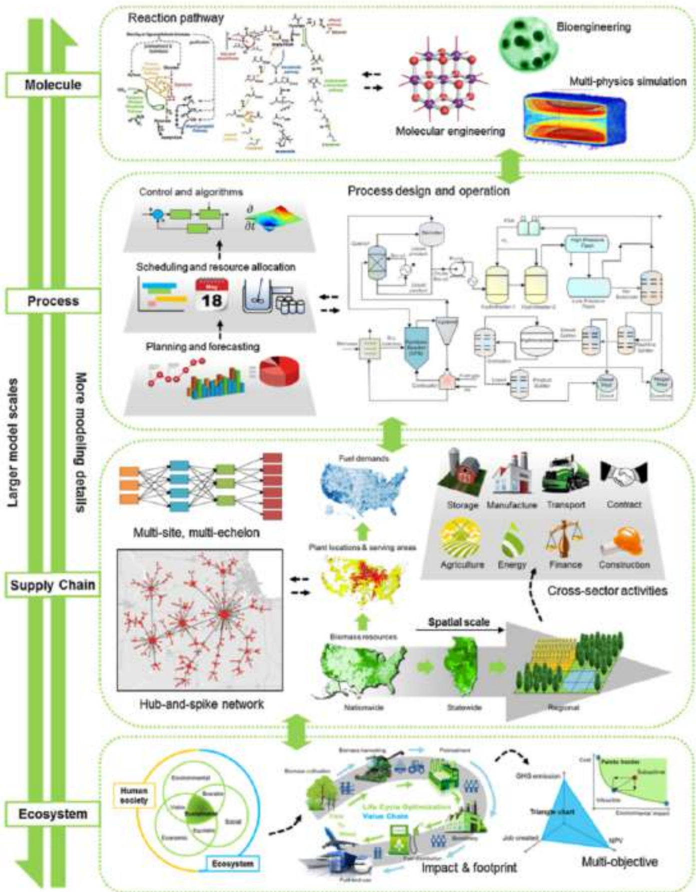

Figure 3.2: Multi-scale modeling and optimization of biofuel supply chains [44].

Related to the different modeling scales described by Yue et al. [142], there are different levels of decision making, which are explained in a paper of De Meyer et al. [44]. De Meyer et al. [44] made an extensive review of studies that investigated the optimization of biofuel supply chains, up to 2013. In their study, they appointed different decision variables to different levels of decision making. A distinction can be made between strategical, tactical, and operational decision making. The decision variables associated with different levels of decision making in the biofuel supply chain are visualized in table 3.1.

Strategic optimization mainly looks into long term investment decisions like sizing and locating refineries or looking into long term feedstock availability [44].

Table 3.1: Different levels of decision making in the supply chain [44].

Decision level	**Strategic**	**Tactical**	**Operational**
Decision variables	*Facility* - Location - Capacity or size - Technology or size	*Inventory planning* - How much to harvest - When to harvest - Inventory control	*Inventory planning* - Day-to-day inventory costs
	Biomass - Sourcing - Allocation between facilities	*Fleet management* - Transport mode - Shipment size - Routing - Scheduling	*Fleet management* - Vehicle planning - Scheduling

3.3. Modeling the biofuel supply chain

Many studies were performed on optimizing the biofuel supply chain for road, aviation, heat, and power purposes. Most of these studies performed case studies on national levels. The highest level found was from a study of Lamers et al. [88] who looked at the development of global trade for solid biomass. They exclusively looked into large-scale heat and power production. He made a similar trade-off by making the simulation less detailed, but on a larger geographical scale to assess the effect of different policy scenarios on international trade.

Lamers et al. [88] use a two-step approach to the allocation problem. First, they create a cost per volume origin/destination matrix. Large seaports located in the import/export regions are used as demand/supply nodes. Consequently, they calculated the total supply costs as a combination of free-on-board prices of feed-stock, the distance between supply and demand node, maximum shipping sizes, and shipping costs. They did not explicitly model hinterland logistics but estimated and included them in the free-on-board price.

Another study looked into the renewable jet fuel supply chain in Europe and was performed by de Jong et al. [43]. They made several scenarios based on varying supply and demand for biomass from competing industries. Using techno-economic data obtained from literature sources and a cost optimization model, they determined the optimal deployment of renewable jet fuel in Europe until 2030.

The studies of Lamers et al. [88] and de Jong et al. [43] are only two examples of many studies that looked into biofuel supply chains. In appendix A, an overview is provided of different studies that modeled biofuel supply chains. All these studies made use of MILP modeling. The reason that MILP modeling is the first choice is the resemblance of the biofuel supply chain with a common facility location optimization problem. As an example, Giarola et al. [67] used an MILP model to optimize a hybrid first/second-generation biofuel supply chain. The model approach of Giarola et al. [67] indicates a modular framework for the modeling of biofuel supply chains, shown in table 3.2. It involves the use of different types of feedstocks, conversion facilities, and transport modes. The same structure as used by Giarola et al. [67], is recognized in all other studies shown in Appendix A.

Table 3.2: Modular framework of biofuel supply chain optimization [67]

Input	**Output**
Geographical distribution of demand centres;	Geographical location of biomass production sites;
Fuel demand over the entire time horizon;	Biomass production rate and feedstock mix to the plant;
Biomass geographical availability;	Biofuel facilities technology selection, location and scale; characterisation of transport logistics;
Geographical location of biomass production sites;	Financial performance of the system over the time horizon;
Biomass production potential for each site;	System impact on global warming.
Biomass production costs as a function of geographical region;	
Technical (yields) and economic (capital and operating costs) parameters as a function of biomass type, production technology and plant scale;	
Environmental burdens of biomass production as a function of biomass type and geographical region;	
Environmental burdens of biofuel production as a function of biomass type and production technology;	
Transport logistics (modes, capacities, distances, availability, environmental burdens and costs);	
Biofuel market characteristics;	
Energy market prices and existing subsidies (green credits).	

While it is now evident how a biofuel supply chain can be modeled, there are various ways to model the sub-processes that are embedded this supply chain, which will be discussed in the following section.

3.4. Modeling the sub processes

It was discussed in the previous section how the marine biofuel supply chain could be modeled using a MILP model. Zooming in on the marine biofuel supply chain, it should also be decided how the sub-processes will be modeled. These processes include the availability of biomass, the demand for biofuel, and all the processes in between. A schematic representation of these sub-processes is shown in figure 3.3. Methods for modeling the three sub-processes shown in figure 3.3 are discussed in the following sub sections.

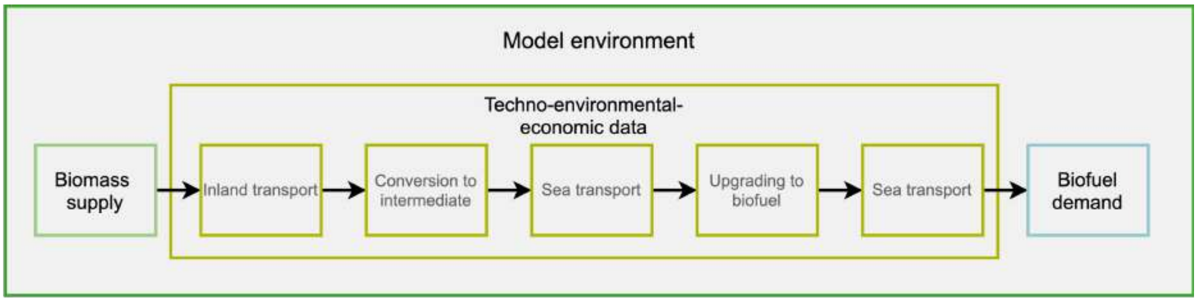

Figure 3.3: Schematic visualization of the sub-processes within the model.

3.4.1. Biomass availability

Tanzer [126] performed a combined techno-economic assessment with a Lifecycle Analysis (LCA) in which she estimated costs and emissions related to biofuel production.

The first phase is mainly about determining the supply capacity of the in-scope feedstocks. In the study of de Jong et al. [43] availability of various types of feedstocks in EU member states was obtained from a study of Elbersen et al. [60]. Tanzer [126] determined the availability of lignocellulosic residues in Scandinavia and Brazil based on national public data sources. Giarola et al. [67] also used national databases to determine domestic biomass availability in Italy.

Because of the large spatial scale of this research and restricted time frame, it is not realistic to model the harvesting process for every feedstock in every region. Therefore, a more data-driven approach is preferred. It can be stated that studies modeling the biofuel supply chain on a strategic level mainly used a data-driven approach to determine feedstock availability, costs, and emissions.

3.4.2. Demand for marine biofuel

Another part of the supply chain that can be seen as a sub-process is the determination of future demand for marine biofuels. To the author's best knowledge, such demand was not earlier determined, seeing that no biofuel supply chain optimization studies focused on the shipping industry before.

Tanzer [126] estimated the marine biofuel demand to be 10% of the total marine bunker demand. She based this estimate on the former EU target of 10% renewable transport energy. Grijpma et al. [70] looked at specific emission reduction targets in Europe and also looked at the potential of biofuels for meeting these targets.

A starting point for determining future marine biofuel demand would be looking into future energy demand for the shipping industry. It was already indicated in the problem statement (section 2.3) that there is much difference between studies forecasting this energy demand. It, therefore, seems that developing such a model would be time-consuming and lead to an uncertain outcome after all.

It is not the objective of this thesis to model the future demand for marine biofuels. It is instead the goal to identify what the potential of drop-in biofuels for reducing GHG emissions caused by shipping might be. Therefore, several demand scenarios can be made to constrain the demand side of the optimization model and analyze the effect on the reduction of emissions.

Outlooks for future energy demand for shipping can be used from IMO's GHG study. Assigning this demand to the chosen bunker hubs can lead to the basis of several demand scenarios.

3.4.3. Well-to-Wake (WtW) costs and emissions

Judging the environmental and economical performance of biofuels needs to be done on a WtW basis. Every phase, shown in figure 3.3, in the supply chain can cause emissions and costs to be allocated to the end product. Modeling this involves the gathering of unit costs and emissions for every distinct phase.

Starting with the harvesting and cultivation of feedstocks. Various studies looked into the estimation of feedstock production costs and related emissions. Alves et al. [20] and Tanzer [126] used several studies to obtain estimations one feedstock prices in Brazil [20, 25, 37, 50]. The process of gathering data for every feedstock in every studied region would be too time-consuming. Therefore, the same approach as the one used by Tanzer [126] could be utilized. She indicated that at source feedstock prices are dependent on the feedstock and the location. She used the source price of various feedstocks obtained from different papers. When data in certain regions for specific feedstocks was not available, she used data of similar feedstocks in neighbouring countries instead. Lamers et al. [88] used cost-supply curves per region, which involved production, processing, and logistic costs. They made different supply scenarios based on sustainability levels. de Jong et al. [43] used cost-supply curves for the selected feedstock types, which were based on the study of Elbersen et al. [60]. To determine GHG emissions related to harvesting of feedstocks, Tanzer [126] used data from eco-invent. She assigned 15% of the emissions related to harvesting of the actual crop to the residues. Giarola et al. [67] determined the emissions related to the harvesting of corn-stover by looking at "the amount of fertilizer required to offset soil nutrients depletion due to stover removal as well as to the diesel usage employed for the harvesting".

Secondly, unit costs and emissions for transport are well known for most transport modes. When the volume/weight of the commodity and the travel distance is known, transport costs and emissions can be calculated. However, transport tariffs vary per region. Estimates for these prices need to be based on the literature. Due to the large spatial scale of this research, a similar approach as that of Lamers et al. [88] can be used to model the transport costs. This approach requires data concerning regional dependent transportation costs for different transport modes. The harvesting site is assumed to be in the geographical center of the supply area.

For the determination of unit costs and emissions related to the processing steps, results from studies that looked into bio-refineries on the molecular and process level can be used [142]. As shown in figure 3.2, refineries can be modeled on different levels. An example of this is a study of Marvin et al. [97]. They studied the optimization of a lignocellulosic biomass-to-ethanol supply chain. To model refineries, they used yields obtained from techno-economic assessments of Humbird and Aden [81]. Leduc et al. [90] also used ethanol yields obtained from a process model in their supply chain optimization. It is concluded that all considered studies that modeled the biofuel supply chain on a strategical level (overview of studies is given in appendix A), modeled the refinery as a black box with product yields obtained from studies that looked into conversion pathways on a process level. Studies that look into these conversion pathways on a process level are mostly techno-economic and life-cycle assessments. Tanzer [126] performed such a techno-economic and life-cycle assessment for all the pathways considered in this thesis. Besides the determination of process yields, these studies also look into life-cycle emissions and the costs of the conversion processes. In most studies, including the study of Tanzer [126], costs and emissions can either be assigned to the operational use or the setting up of the refinery.

Tanzer [126] indicated that emissions related to the operational use of the refinery are mainly caused by "flue gasses and the upstream impacts of chemicals, water, wastewater, and utilities during process modeling". She also showed that refineries produce electricity as a side product. Therefore, the emissions should be allocated between the production of electricity and marine biofuel. Tanzer [126] deducted the impact that would be caused by the production of the same amount of electricity in a stand-alone facility from the total impacts. The remaining impacts can be allocated to the production of marine biofuel. A similar study was performed by Tews et al. [127], who looked into fast pyrolysis and HTL with lignocellulosic residues. Tanzer [126] neglected the emissions caused due to the setting up of a new refinery.

Lastly, because the conversion pathways are not yet commercially available, the refineries also do not exist. As shown in table 3.1, determining facility locations and capacities is one of the goals of strategically modeling the supply chain. Therefore, running the optimization model needs to give insight into the future refinery locations and capacities, as also stated in the last sub-research question.

The recommended approach for the modeling of refineries is thus to use yields, costs, and emission estimations from other process-level studies. Running the optimization model with technological learning constraints should result in refinery locations and sizes.

3.5. Knowledge gap

Many studies indicated that biofuels are a promising solution for reducing emissions in shipping [26, 27, 55, 63, 70, 78]. They also addressed that there are some barriers to the use of biofuels in the maritime industry. The main barriers that were mentioned were the fuel price and the supply guarantee [78].

Although the above-mentioned barriers are well known, only a little research is performed into what the future demand for marine biofuels might be and how this demand will align with global feedstock availability. Like stated earlier, we are therefore not able to identify the global emission reduction potential of drop-in biofuels alone. New biofuel pathways are emerging, creating an opportunity for more abundant and cheaper feedstocks to be used. The relation between the regional availability of these feedstocks, the introduction of new conversion pathways, and the future demand of biofuels in the shipping industry has, to the best knowledge of the author, not been studied before.

It is expected that regulations on GHG emissions caused by the shipping industry will be implemented to make sure the targets of the IMO are achieved [27, 34, 78]. Such global or regional regulations might involve mandatory admixture rates of biofuels. However, it is uncertain what the impact of such regulatory scenarios on GHG emissions will be. Increasing demand for marine biofuels could impose the need for long-distance trade of biofuels between regions. To assess the potential GHG emission savings caused by the usage of biofuels, the entire supply chain from WtW needs to be considered. Such an analysis would clarify uncertainties about the potential of drop-in biofuels for the maritime industry and support regulatory decisions.

Many studies optimized biofuel supply chains (annex A.1), but non of them looked specifically into the potential biofuel demand of the shipping industry. The marine biofuel supply chain differs from other studied sectors like aviation [43]. Shipping operators have the opportunity to strategically choose where they refuel [116]. This is mainly caused by the low bunker frequency of seagoing ships. Therefore, the marine biofuel supply chain should be modeled on a global level.

No research was found that addressed the uncertainty concerning future demand for marine biofuel and linked this to the availability of biomass feedstocks. Additionally, the impact that the increasing use of drop-in biofuels in the maritime industry could have on total GHG savings is unknown. To take away this uncertainty, it is required to model and optimize this marine drop-in biofuel supply chain.

This study aims to fill this gap by assessing the locations and quantities of the most promising biomass feedstocks. On the other hand, scenarios for regional marine biofuel demand will be developed. Optimizing supply and demand will give insight into the potential of biofuels for the maritime industry. This insight will consist out of well-to-tank emission and costs associated with the delivery of biofuels in shipping regions.

The results will indicate the development of future biofuel trade flows. It will also identify to what extent the regional availability of feedstocks and the scalability of future bio-refineries are limiting factors for the supply of biofuels to the maritime industry. It is aimed to model the influence of possible global and regional prescriptive blending requirements.

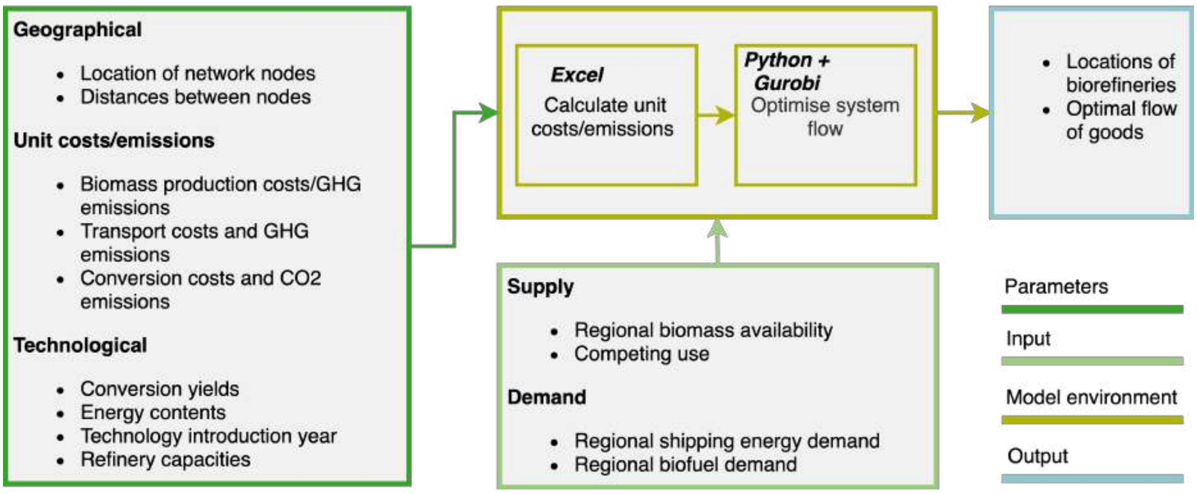

Figure 3.4: Schematic visualization of the optimization model.

3.6. Model selection

After studying the proposed literature and assessing the knowledge gap, a substantiated reasoning can be formulated on how to model the marine biofuel supply chain and its sub-processes.

- **Structure of the marine biofuel supply chain**
  - The structure of the marine biofuel supply chain will be two-stage. This entails a physical separation between processing and upgrading facility.
- **Level of modeling:**
  - The global marine biofuel supply chain needs to be modeled on a strategic level.

- **How to model**
  - The marine biofuel supply chain will be modeled using a MILP model.
- **Modeling of the sub-processes**
  - All sub-processes will be modeled using a data driven approach.

A schematic representation of this model is visualized in figure 3.4.

4
MILP model

This chapter elaborates on the previous chapter. The previous chapter answered the following sub-research question.

How are biofuel supply chains previously studied and modeled?

In this chapter, the model previously described model is developed. As discussed in the literature review, the marine biofuel supply chain will be modeled using a MILP model. The model has two objective functions in which both economic and environmental performance are taken into account.

The structure of this chapter will be as follows. Section 4.1 introduces a general minimum cost facility location problem. In section 4.2, the mathematical formulation of the economical and environmental optimization model is discussed. Section 4.3 discusses the constraint to which the model is subjected.

4.1. General discrete facility location problem

According to [142], optimization of a biofuel supply chain shows many resemblances with a facility location problem. In this case, facilities can be seen as upgrading facilities for the conversion of intermediate bioenergy carriers into the transport fuel. The model used in this thesis is a discrete facility location problem, which indicates that the refinery candidate locations are already given upfront.

The general discrete facility location problem contains the following indices and parameters.

- i = index for locations i = 1...M
- j = index for customers j = 1...N
- f_i = fixed costs related to the opening of a facility at location i
- d_j = demand for customer j
- p_j = selling price
- q_i = production costs
- t_{ij} = transport costs
- c_{ij} = variable costs between location i and customer j

And contains the following decision variables.

- y_i = facility at location i (y_i = binary)
- x_{ij} = customer j served from i

It should be noted that this general discrete facility location problem with set up costs only considers demand for one commodity. The above assumptions are used to formulate the objective function, which is to minimize total system costs:

$$MIN \sum_{i \in I} \sum_{j \in J} c_{ij} \cdot x_{ij} + \sum_{i \in I} f_i \cdot y_i. \tag{4.1}$$

This objective function is subjected to several constraints. Equation (4.2) ensures that the demand of customer j is fulfilled.

$$\sum_{i \in I} x_{ij} = 1 \tag{4.2}$$

Eq. (4.3) ensures that customer j can only be served from facility i, if there is a facility located at that node.

$$y_i - x_{ij} \geq 0 \tag{4.3}$$

Because x_{ij} represents a continuous share of the demand d_j that is fulfilled from facility $i \in I$, the following constraint is formulated:

$$0 \leq x_{ij} \leq 1 \quad \forall i, j. \tag{4.4}$$

This general discrete facility location model is used as a basis for the development of a model that represents the strategical optimization of the marine biofuel supply chain. Further development of the model is discussed in the next section.

4.2. Multi-objective optimization

Using the previously explained general discrete facility location problem, a model formulation can be developed. A schematic representation of the studied network is shown in figure 4.1.

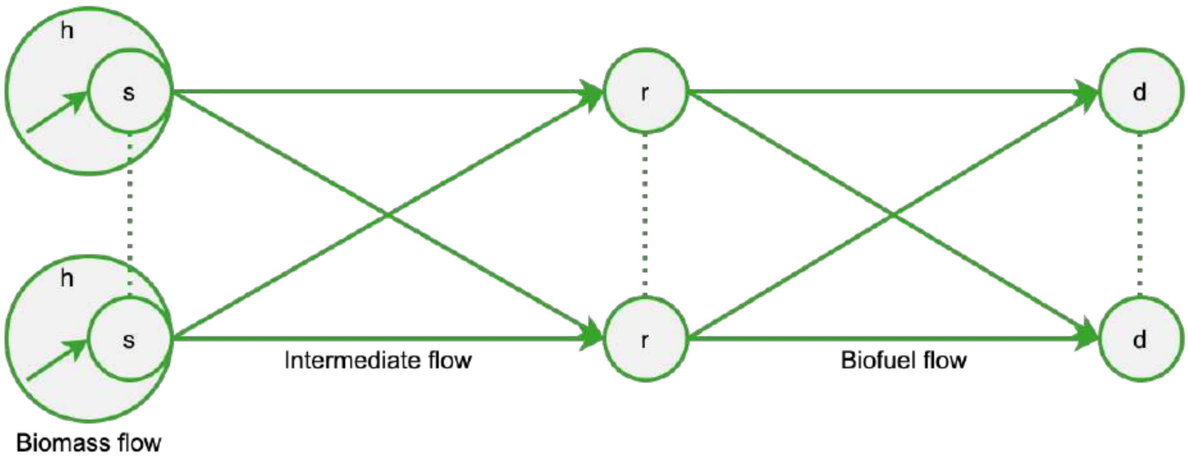

Figure 4.1: Schematic representation of the marine biofuel supply chain network. Partly adapted from De Jong et al. [41].

This network is slightly different than the model discussed in section 4.1. Firstly, multiple commodities flow within the network. Secondly, the refinery locations serve as transshipment nodes. Lastly, the model serves two objectives.

To start, the model consists of eight sets. Following the general set-up of the marine biofuel supply chain, there are three types of nodes. These nodes can be categorized into supply nodes S, refinery candidate location nodes R, and demand nodes D. At every supply node in S, there is an availability of the set of biomass types B. Inland transport costs of the biomass types B are discretized using supply steps I. The elements of the set of biomass types B can be processed inside the supply areas H to an intermediate product of the set J. These intermediates J can be upgraded inside a refinery of size P into a biofuel from the set G. The optimization is performed over a time horizon T. The entire model description is given in the nomenclature presented in figure 4.2.

Nomenclature

Sets

- B Set of biomass feedstocks
- D Set of demand nodes
- G Set of end products
- H Set of regions
- I Set of supply steps
- J Set of intermediate products
- P Set of plant sizes
- R Set of candidate refinery nodes
- S Set of supply nodes
- T Set of time periods

Decision Variables

- BF_{sbjit} Used amount of biomass $b \in B$ of supply step $i \in I$ at supply node $s \in S$ to produce intermediate product $j \in J$ during time period $t \in T$. (PJ)
- FF_{rdgt} Flow of biofuel $g \in G$ between refinery node $r \in R$ and demand node $d \in D$ during time period $t \in T$. (PJ)
- IF_{srjt} Flow of intermediate $j \in J$ between supply node $s \in S$ and refinery node $r \in R$ during time period $t \in T$. (PJ)
- Y_{rgpt} Variable that indicates whether a refinery of size $p \in P$ producing biofuel $g \in G$ at refinery node $r \in R$ is built during time period $t \in T$.

Parameters

- γ_{jg} Conversion yield from intermediate product $j \in J$ to biofuel $g \in G$.
- λ_{sbi}^{high} Upper boundary for biomass type $b \in B$ in supply step $i \in I$ at supply node $s \in S$.
- λ_{sbi}^{low} Lower boundary for biomass type $b \in B$ in supply step $i \in I$ at supply node $s \in S$.
- ω_{bj} Conversion yield from biomass $b \in B$ to intermediate $j \in J$.
- ρ_b Ratio between density of biomass type $b \in B$ and the maximum freight density.
- C Total system costs over the entire studied period.
- C_t^I Costs related to the intermediate bio-energy carrier during $t \in T$.
- C_t^T Costs related to sea transport during $t \in T$.
- C_t^U Costs related to the upgrading process during $t \in T$.
- C_t^{FT} Costs related to sea transport of the biofuel during $t \in T$.
- C_t^{IB} Cost of biomass during $t \in T$.
- C_t^{IP} Costs of processing the intermediate bio-energy carrier to a biofuel $t \in T$.
- C_t^{IT} Costs related to sea transport of the intermediate product during $t \in T$.
- C_t^{IT} Costs related to the inland transport of the intermediate bio-energy carrier during $t \in T$.
- C_t^{UF} Fixed costs related to the upgrading process during $t \in T$.
- C_t^{UV} Variable costs related to the upgrading process during $t \in T$.
- df_{dt} Biofuel demand at demand location $d \in D$ during time period $t \in T$. (PJ)
- E Total system emissions over the entire studied period.
- E_t^I Emissions related to the intermediate product during $t \in T$.
- E_t^T Emissions related to sea transport during $t \in T$.
- E_t^U Emissions related to the upgrading phase during $t \in T$.
- E_t^{IB} Emissions related to cultivation and harvesting of biomass during $t \in T$.
- E_t^{IP} Emissions related to the processing phase during $t \in T$.
- E_t^{IT} Emissions related to the inland transport of biomass during $t \in T$.
- E_t^{TI} Emissions related to the sea transport of the biofuel products during $t \in T$.
- E_t^{TI} Emissions related to the sea transport of the intermediate products during $t \in T$.
- ef_b Emissions related to cultivation of feedstock $b \in B$. (kton CO2-eq/PJ)
- eit_{si} Emissions related to the inland transport at supply node $s \in S$ in supply step $i \in I$. (kton CO2-eq/kton)
- ep_j Emissions related to the conversion of biomass $b \in B$ to intermediate $j \in J$. (kton CO2-eq/PJ)
- est_{sr} Emissions related to the sea transport in between nodes. (kton CO2-eq/kton)
- eu_g Emissions related to the upgrading to biofuel $g \in G$. (kton CO2-eq/PJ)
- $fcap_{sbt}$ Availability of feedstock $b \in B$ at supply node $s \in S$ during time period $t \in T$. (PJ)
- $lhvb_b$ Lower heating value of biomass type $b \in B$. (MJ/kg)
- $lhvg_g$ Lower heating value of biofuel $g \in G$. (MJ/kg)
- $lhvj_j$ Lower heating value of intermediate product $j \in J$. (MJ/kg)
- $rcap_{pg}$ Capacity of a refinery of size $p \in P$ producing fuel $g \in G$. (PJ)
- ubc_{sbt} Unit costs of biomass $b \in B$ at supply node $s \in S$ during time period $t \in T$. (mln €/PJ)
- ufc_{rgpt} Annualized fixed costs of running a refinery of size $p \in P$ producing fuel $g \in G$ at refinery node $r \in R$ in time period $t \in T$. (mln €/5 years)
- $uitc_{sbt}$ Unit costs for inland transport of biomass $b \in B$ to supply node $s \in S$ during time period $t \in T$. (mln €/kton)
- upc_{sbjt} Unit costs of producing intermediate $j \in J$ from biomass $b \in B$ at supply node $s \in S$ during time period $t \in T$. (mln €/PJ)
- $ustc_{sr}$ Unit overseas transport costs between supply node $s \in S$ and refinery node $r \in R$. (mln €/kton)
- uvc_{rgt} Variable costs related to running a refinery producing biofuel $g \in G$ at refinery node $r \in R$ during time period $t \in T$. (mln €/PJ)

Figure 4.2: The model nomenclature.

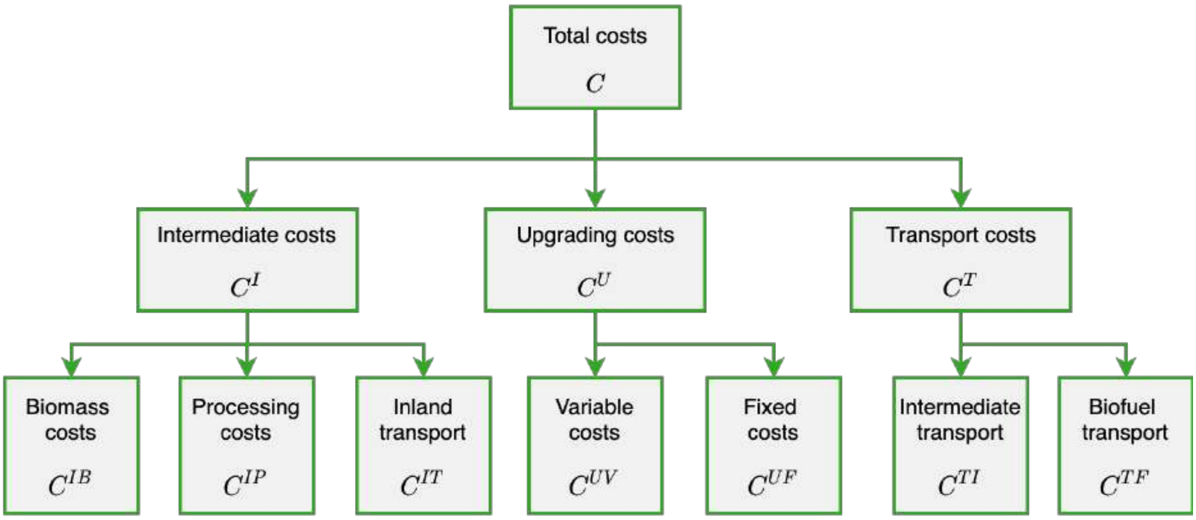

Figure 4.3: Division of costs in the marine biofuel supply chain.

4.2.1. Economic objective

The economic objective is to minimize total system costs. These total system costs are dependent on four decision variables. Three of these decision variables are related to the flow inside the system and are continuous. The fourth is an integer variable which indicates how many refineries of size $p \in P$ and type $g \in G$ are located at refinery node $r \in R$. The decision variable BF_{sbjit} indicates the amount of biomass of type $b \in B$ of supply interval $i \in I$ that is processed into intermediate $j \in J$ at supply node $s \in S$ during time period $t \in T$. IF_{srjt} specifies the flow of intermediate product $j \in J$ that is transported from supply node $s \in S$ to refinery node $r \in R$ during time period $t \in T$. FF_{rdgt} reveals the amount of biofuel type $g \in G$ that flows between refinery node $r \in R$ and demand node $d \in D$ during time period $t \in T$. The final decision variable, Y_{rgpt}, indicates whether a refinery of size $p \in P$, producing fuel $g \in G$ is operational at candidate location $r \in R$ during time period $t \in T$. These four decision variables, combined with several parameters, are used to formulate the economic objective function:

$$Obj^{eco} = Min.C \tag{4.5}$$

Like visualized in figure 4.3, the costs can be separated into three parts, the costs of the intermediate product, the costs of upgrading the intermediate to a biofuel and the cost of sea transport:

$$C = \sum_{t \in T} (C_t^I + C_t^U + C_t^T) \tag{4.6}$$

Costs of the intermediate product are dependent on the region and the feedstocks that they are made from. It is assumed that a refinery in a certain area only uses feedstocks that originate from that area. These costs can again be subdivided into three parts. The costs related to the intermediate product consist out of feedstock, processing and inland transport costs:

$$C_t^I = C_t^{IB} + C_t^{IP} + C_t^{IT} \tag{4.7}$$

The feedstock costs are the costs of the different types of biomass $b \in B$ at location $s \in S$ during period $t \in T$:

$$C_t^{IB} = \sum_{s \in S} \sum_{b \in B} \sum_{j \in J} ubc_{sb} \cdot BF_{sbjit} \quad \forall t \in T \tag{4.8}$$

The processing costs are expressed as the costs related to producing intermediate product $j \in J$ from biomass type $b \in B$ at supply location $s \in S$ and are displayed in Equation (4.9). An assumption is made that the processing costs are only dependent on the area in which the processing is performed. Spatial optimization of the processing facilities is outside the scope of this thesis. The reason for this is the assumption that long-distance transport of low density biomass would not be efficient.

$$C^{IP} = \sum_{s \in S} \sum_{b \in B} \sum_{j \in J} (upc_{sj} \cdot IF_{srjt}) \quad \forall t \in T \tag{4.9}$$

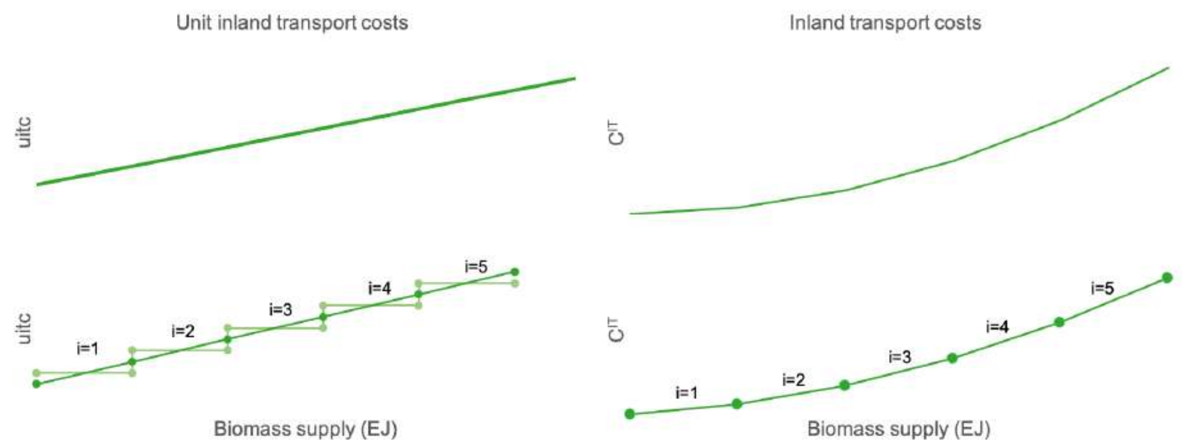

Figure 4.4: Visualization of the piece-wise linearization used to mimic the increasing inland transport costs.

The third part of C_t^I includes the inland transport of the biomass to the processing facility. Generally, the supply costs of biomass are depicted as cost/supply curves. Regional biomass costs rise when the required supply increases. Initially, biomass that is nearest to the processing facility, and most easy to gather, is used. When demand increases, biomass that is more difficult to access and further from the processing facility will be used, increasing transport distance and costs consequently. To mimic this effect, inland transport costs are expressed as a linear function of the biomass flow inside the supply areas. However, this property induces a non-linear relationship between the biomass flow and inland transport costs. To solve this, the function is split up into five discrete cost segments for every biomass type and region combination.

These five segments are indicated by $i \in I$ and the method is visualized in graph 4.4. Every $i \in I$ represents a certain value for $uitc_{si}$. Using the above described method, the total inland transport costs of biomass for every $t \in T$ can be calculated using the expression shown in Equation (4.10). Seeing that biomass is usually of low density, ρ_b represents a ratio between the density of biomass $b \in B$ and the density allowed to reach the maximum freight load.

$$C_t^{IT} = \sum_{s \in S} \sum_{b \in B} \sum_{j \in J} (uitc_s \cdot \rho_b \cdot \frac{BF_{sbjit}}{lhvb_b}) \quad \forall t \in T \tag{4.10}$$

The second cost item includes the costs that are related to setting up and operating an upgrading facility. These costs can be divided into variable and fixed costs:

$$C_t^U = C_t^{UV} + C_t^{UF} \quad \forall t \in T \tag{4.11}$$

In the optimization model of Lin et al. [93], the Operational Expenditures (OPEX) were considered to be independent of the refinery capacity. In this model, the same assumption is made. However, OPEX are dependent on the location in which the refinery operates. The OPEX are calculated separately from the feedstock costs, which were already included in C_t^{IB}.

In general, part of the OPEX can be seen as variable costs and another part as fixed costs. C^{UV} only includes the variable part of the OPEX, which is dependent on the produced amount of biofuel:

$$C_t^{UV} = \sum_{r \in R} \sum_{g \in G} \sum_{d \in D} uvc_{rgt} \cdot FF_{rdgt} \quad \forall t \in T \tag{4.12}$$

In Equation (4.12), uvc_{rgt} represents the OPEX per energy output of biofuel $g \in G$ at location $r \in R$ during time period $t \in T$. The Capital Expenses (CAPEX) are annualized over the lifetime and are added to the fixed part of the refinery OPEX. This is expressed in Equation (4.13):

$$C_t^{UF} = \sum_{r \in R} \sum_{g \in G} \sum_{p \in P} ufc_{rgpt} \cdot Y_{rgpt} \quad \forall t \in T \tag{4.13}$$

The decision variable Y_{rgpt} is an integer that indicates if a plant of size $p \in P$ producing fuel $g \in G$ at location $r \in R$ is operational during time period $t \in T$.

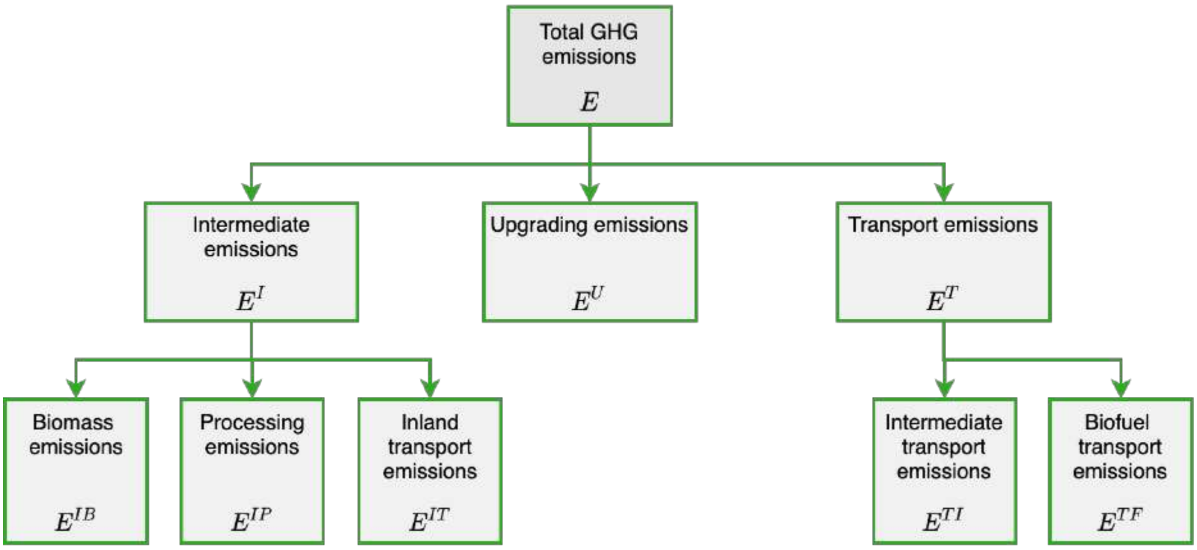

Figure 4.5: Categorization of emissions over the entire supply chain.

Lastly, transport costs are divided into the costs for the transportation of the intermediate products and the end products, which is expressed in Eq. (4.14). Inland transport costs were already included in the costs related to the intermediate product.

$$C_t^T = C_t^{IT} + C_t^{FT} \quad \forall t \in T \tag{4.14}$$

Transport costs related to the intermediate product are expressed as:

$$C_t^{IT} = \sum_{s \in S} \sum_{r \in R} \sum_{j \in J} (ustc_{sr} \cdot \frac{IF_{srjt}}{lhvj_j}) \quad \forall t \in T \tag{4.15}$$

Transport costs related to the biofuel are expressed as:

$$C_t^{FT} = \sum_{r \in R} \sum_{d \in D} \sum_{g \in G} (ustc_{rd} \cdot \frac{FF_{rdgt}}{lhvg_g}) \quad \forall t \in T \tag{4.16}$$

4.2.2. Environmental objective

The environmental objective is to minimize the total GHG emissions related to the supply of marine biofuels. The same decision variables as introduced in the previous section are used for environmental optimization. To determine the GHG emissions of the marine biofuel supply chain, the method of Giarola et al. [67] is used as a starting point. The supply chain emissions are separated into different phases. The objective function that follows from that is stated in Equation (4.17).

$$Obj^{env} = Min.E \tag{4.17}$$

These emissions can be divided into the elements depicted in figure 4.5. Which leads to the following objective function:

$$E = \sum_{t \in T} (E_t^I + E_t^U + E_t^T) \tag{4.18}$$

Starting with the emissions that are caused by the production of the intermediate bioenergy carrier. These emissions can be split up into emissions caused by harvesting, gathering and processing of the feedstocks. Also inland transport of the feedstock needs to be considered. This results in the following expression:

$$E_t^I = E_t^{IB} + E_t^{IP} + E_t^{IT} \quad \forall t \in T \tag{4.19}$$

Emissions caused by harvesting and gathering of the feedstocks are assumed to be proportional to the flow of biomass inside the supply regions:

$$E_t^{IB} = \sum_{s \in S} \sum_{b \in B} \sum_{j \in J} BF_{sbjt} \cdot ef_{sb} \quad \forall t \in T \tag{4.20}$$

Furthermore, the feedstock will be processed into an intermediate energy carrier. The emissions related to this conversion are proportional to the amount of intermediate produced:

$$E_t^{IP} = \sum_{s\in S}\sum_{r\in R}\sum_{j\in J} IF_{srjt}\cdot ep_{sj} \quad \forall t \in T \tag{4.21}$$

The inland transport costs are considered as a constant for every region and biomass type. An average distance is assumed dependent on the size of the region. Furthermore, the same approach as explained in 4.2.1 is used to simulate increasing inland transport emissions due to increasing distance when more supply is needed:

$$E_t^{IT} = \sum_{s\in S}\sum_{b\in B}\sum_{j\in J} BF_{sbjt}\cdot \frac{eit_{sb}}{lhvb_b} \quad \forall t \in T \tag{4.22}$$

For the emissions related to the upgrading of the intermediate bioenergy carrier to the eventual biofuel, the following expression is used:

$$E_t^{U} = \sum_{r\in R}\sum_{d\in D}\sum_{g\in G} FF_{rdgt}\cdot eu_{rg} \quad \forall t \in T \tag{4.23}$$

Additionally, there are emissions associated with the overseas transport of both the intermediate bioenergy carrier and the biofuel:

$$E_t^{T} = E_t^{TI} + E_t^{TF} \tag{4.24}$$

These emissions are caused by the combustion of fossil products of the tankers which transport the goods. In the future, renewable fuels may be used for this transport. The effect of this change in energy source on transport emissions will be further elaborated on in the sensitivity analysis (8.2. Both the flow of the intermediate products and the biofuel products are multiplied with an emission factor that is dependent on the distance between the nodes:

$$E_t^{TI} = \sum_{s\in S}\sum_{r\in R}\sum_{j\in J} IF_{srjt}\cdot est_{sr} \quad \forall t \in T \tag{4.25}$$

$$E_t^{TF} = \sum_{r\in R}\sum_{d\in D}\sum_{g\in G} FF_{rdgt}\cdot est_{rd} \quad \forall t \in T \tag{4.26}$$

4.3. Model constraints

In this section the constraints, that the model is subjected to, are discussed. Different types of constraints are used in order to make sure the model comes up with viable solutions. The various constraints are discussed in the coming subsections.

4.3.1. Non-negativity constraints

Firstly, all four decision variables are not allowed to take on negative values. If these constraints are not defined, the model will minimize the problem, coming up with solutions below zero:

$$BF_{sbjit} \geq 0 \quad \forall s \in Sb \in B, j \in J, i \in I, t \in T \tag{4.27}$$

$$IF_{srjt} \geq 0 \quad \forall s \in S, r \in R, j \in J, t \in T \tag{4.28}$$

$$FF_{rdgt} \geq 0 \quad \forall r \in r, d \in D, g \in G, t \in T \tag{4.29}$$

$$Y_{rgpt} \geq 0 \quad \forall r \in R, g \in G, p \in P, t \in T \tag{4.30}$$

4.3.2. Flow equilibrium constraints

Secondly, flow equilibrium constraints are required to ensure that the flow of goods stays consistent throughout the simulation. Equation (4.31) ensures equilibrium in every supply node between biomass flow in and intermediate flow out.

$$\sum_{b\in B}(BF_{sbjit}\cdot \omega_{bj}) - \sum_{r\in R} IF_{srjt} = 0 \quad \forall s \in S, t \in T, j \in J \tag{4.31}$$

Equation (4.32) is established to ensure equilibrium in all refinery nodes.

$$\sum_{s\in S}\sum_{j\in J}(IF_{srjt}\cdot \gamma_{jg}) - \sum_{d\in D} FF_{rdgt} = 0 \quad \forall r \in R, g \in G, t \in T \tag{4.32}$$

An additional constraint is used to prevent flow from going through nodes where no refinery is operational. For this purpose, the big-M method is used. M represents a new parameter to which a large number is assigned. Hence, a yes or no decision can be formulated:

$$\sum_{p\in P} Y_{rgpt} \cdot M \geq \sum_{d\in D} FF_{rdgt} \quad \forall g \in G, r \in R, t \in T \tag{4.33}$$

4.3.3. Capacity constraints

To ensure that the global biomass availability is not exceeded, per region a constraint is required that limits the amount of biomass used by all ports in that region. For every distinct region in H a separate constraint is composed, shown in Equation (4.34).

$$\sum_{j\in J} BF_{sbjt} \leq fcap_{hbt} \quad \forall h \in H, s \in S, t \in T, b \in B \tag{4.34}$$

Additionally, the refinery capacity at a refinery node $r \in R$ may not be exceeded. Also, only intermediate flow can go through refinery node $r \in R$ if a plant opened at that location. When there is no capacity at a refinery node $r \in R$, the right-hand side of equation 4.35 becomes zero, forcing the intermediate flow through that node to be zero.

$$\sum_{s\in S}\sum_{j\in J} (IF_{srjt} \cdot \gamma_{jg}) \leq \sum_{p\in P} (rcap_{pg} \cdot Y_{rgpt}) \quad \forall r \in R, g \in G, t \in T \tag{4.35}$$

Equation (4.36) of this minimum cost flow - facility location problem is that the the sum of the fuel flows to the demand nodes equals the demand in that specific node. This constraint can be written as follows:

$$\sum_{r\in R}\sum_{g\in G} FF_{rdgt} = df_{dt} \quad \forall d \in D, t \in T \tag{4.36}$$

Additionally, to make the linearization of the inland transports costs, discussed in 4.2.1, possible, limits for the amount of biomass taken from a particular supply step need to be set up. Therefore, two extra parameters need to be included in the model, λ_{sbi}^{low} and λ_{sbi}^{high} indicating the lower and upper limits of the supply steps. Consequently, the following constraints are set up to ensure the correct price is paid for the amount of supply used:

$$\sum_{j\in J} BF_{sbjit} \geq \lambda_{sbi}^{low} \quad \forall s \in S, b \in B, i \in I, t \in T \tag{4.37}$$

$$\sum_{j\in J} BF_{sbjit} \leq \lambda_{sbi}^{high} \quad \forall s \in S, b \in B, i \in I, t \in T \tag{4.38}$$

4.3.4. Refinery investment constraints

Constraints are required to ensure that when a refinery is operational, it stays active for a given period. In the model, it is assumed that only one refinery of type $g \in G$ can be operational at every refinery node $r \in R$ during $t \in T$. However, the scale of the refinery may vary. This constraint is optional, if it turns out that, to fulfill the demand, more refineries per location are needed, this constraint will be dropped.

$$\sum_{p\in P} Y_{rgpt} \leq 1 \quad \forall r \in R, g \in G, t \in T \tag{4.39}$$

Equation (4.40) ensures that if a refinery is operational during time period $t \in T$, it can only grow to a bigger facility in the next time period, or it stays the same size. This allows for the possibility to expand a refinery over time.

$$\sum_{p\in P} (Y_{rgpt-1} \cdot rcap_{pg}) \leq \sum_{p\in P} (Y_{rgpt} \cdot rcap_{pg}) \quad \forall r \in R, g \in G, t \in T \tag{4.40}$$

4.3.5. Additional constraints

To add some additional features to the model, optional constraints can be implemented. Equation (4.41) can be used to prohibit a conversion technology to be used in a certain period. Some conversion pathways might become mature in the far future, while others may be used from the start. In this case, t^* is the time period in which the conversion technology g^* is not available.

$$\sum_{r\in R}\sum_{d\in D} FF_{rdg^*t^*} = 0 \tag{4.41}$$

Additionally, some fuels might be subjected to a blend wall. This could be implemented by using a constraint that prohibits exceeding this blend wall. If a blend limit is imposed on fuel g^* and the blend limit is expressed as $blendlim$, than that constraint would look as follows:

$$\sum_{r \in R} FF_{rdg^*t} \leq \text{blendlim} \quad \forall d \in D, t \in T \tag{4.42}$$

Lastly, it is assumed that if a product is gaseous it can not be transported. In this case, the amount of biomass used for the production of intermediate j* in a certain node should be equal to the amount of intermediate j* used for the production of biofuel in that same node:

$$\sum_{i \in I} \sum_{b \in B} BF_{sbj^*it} = IF_{ssj^*t} \quad \forall s \in S, t \in T \tag{4.43}$$

5

Biomass supply

The goal of this chapter is to estimate the regional amount of biomass that is available for the production of marine biofuels, now, and in the future.

Where are the in-scope feedstocks located and how much is there available for the production of marine biofuel?

To achieve this goal, the following method is used, which is also depicted in figure 5.1.

1. **Identify the regional amount of biomass**: This is done by consulting literature on this topic. Every feedstock, region, and time-period is taken into account during this analysis.
2. **Identify competing use**: Various data sources are used to make a realistic projection of other industries that use biomass. Three competing industries are taken into consideration, traditional heat, renewable heat and power and the remaining transport sectors (excluding the shipping sector).
3. **What is left?**: Deduct competing uses from the available regional supply.

Assessing the regional availability of biomass resources that will be available for the production of marine biofuels, is a significant challenge. Multiple studies tried to determine the global availability of biomass. However, the large ranges in these potentials, uncover the associated uncertainties [83]. Additionally, it is uncertain what the future use of competing industries will be. To capture this uncertainty, two availability

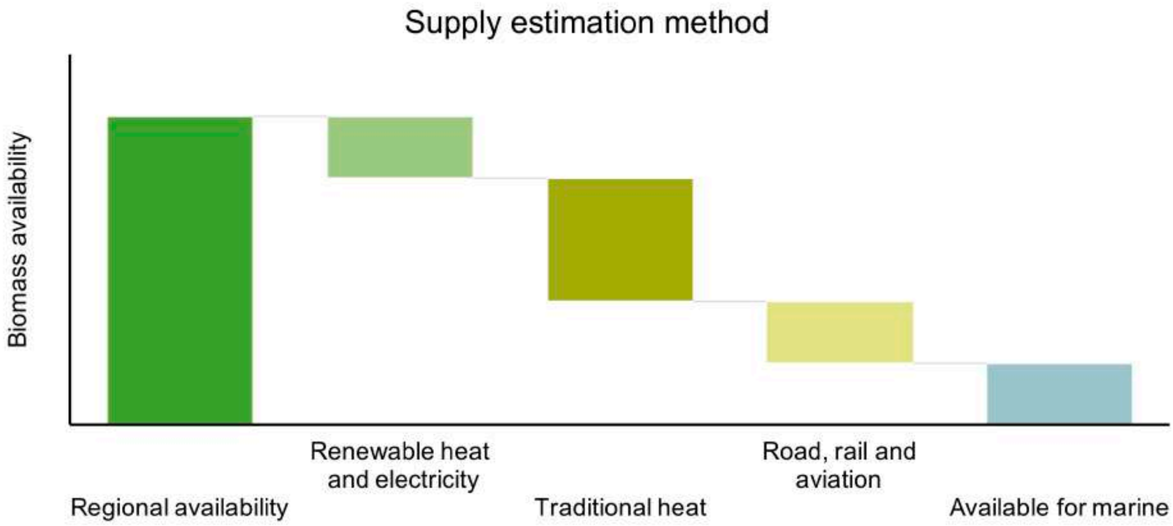

Figure 5.1: Used method for determining available biomass.

	LOW AVAILABILITY	HIGH AVAILABILITY
5.2.1 Oil crops	• Average oil crop production growth • High competition from road, rail and aviation	• Higher production rate of oil crops • Road electrifies, lower competition
5.2.2 Waste oils	• Conventional UCO collection system	• Increasingly efficient UCO collection • Road electrifies, lower competition
5.2.3 Agricultural residues	• Low scenario of CE Delft and IRENA • Growing competition from heat and power	• High scenario of CE Delft and IRENA • Steady competition from heat and power
5.2.4 Forestry residues	• Low scenario of CE Delft and IRENA • Growing competition from heat and power	• Low scenario of CE Delft and IRENA • Steady competition from heat and power
5.2.5 Energy crops	• Low scenario of IRENA • Growing competition from heat and power	• High scenario of IRENA • Steady competition from heat and power
5.2.6 Solid waste	• Average population growth rate • Solid waste disposal rate of IRENA	• Higher population growth rates • More efficient solid waste disposal system
5.2.7 Liquid waste	• Decreased livestock growth rate • Average population growth rate	• Current livestock growth based on historical data of FAO • Higher population growth rate

Figure 5.2: Context of supply scenarios used in this study.

scenarios are developed, which are further explained in figure 5.2. Section 5.1 elaborates on the regional availability per feedstock per period. Consequently, section 5.2 determines the amount of biomass that will be used by competing users. Section 5.3 gives an overview of the resulting regional available biomass for the marine industry for both scenarios. This section also covers the supply scenarios that are used in the remainder of this thesis.

5.1. Regional biomass availability

In the following sections, the regional availability of the in-scope biomass feedstocks is determined. Currently, the total use of solid biomass (mostly forestry and agricultural products) for energy is in the range of 53 and 79 EJ per year [82, 92]. The World Bioenergy Association (WBA) estimated the use of biomass to be around 55.6 EJ in 2017. Of this total use, 2.52 EJ consisted of municipal and industrial waste and 48.2 EJ of solid biofuels like agricultural and forestry products.

The results for the two scenarios are already depicted in figures 5.3 and 5.4. Discussion of the method used to assess the availability are presented per feedstock in sections 5.1.1-5.1.7. Supplementary information is given in Appendix B.1, for a more comprehensive insight in the methods and results.

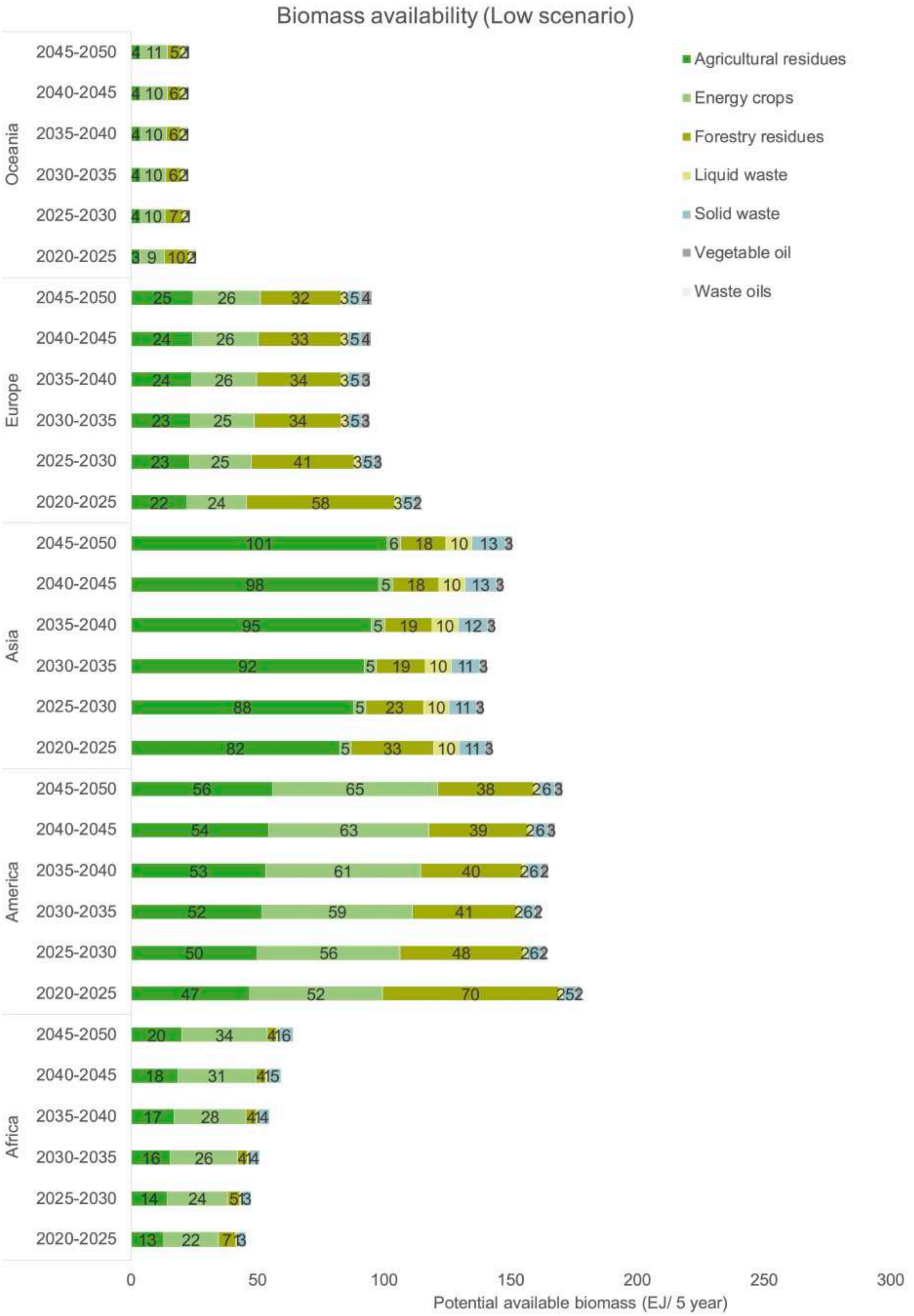

Figure 5.3: Theoretically available biomass in the Low Supply (LS) scenario.

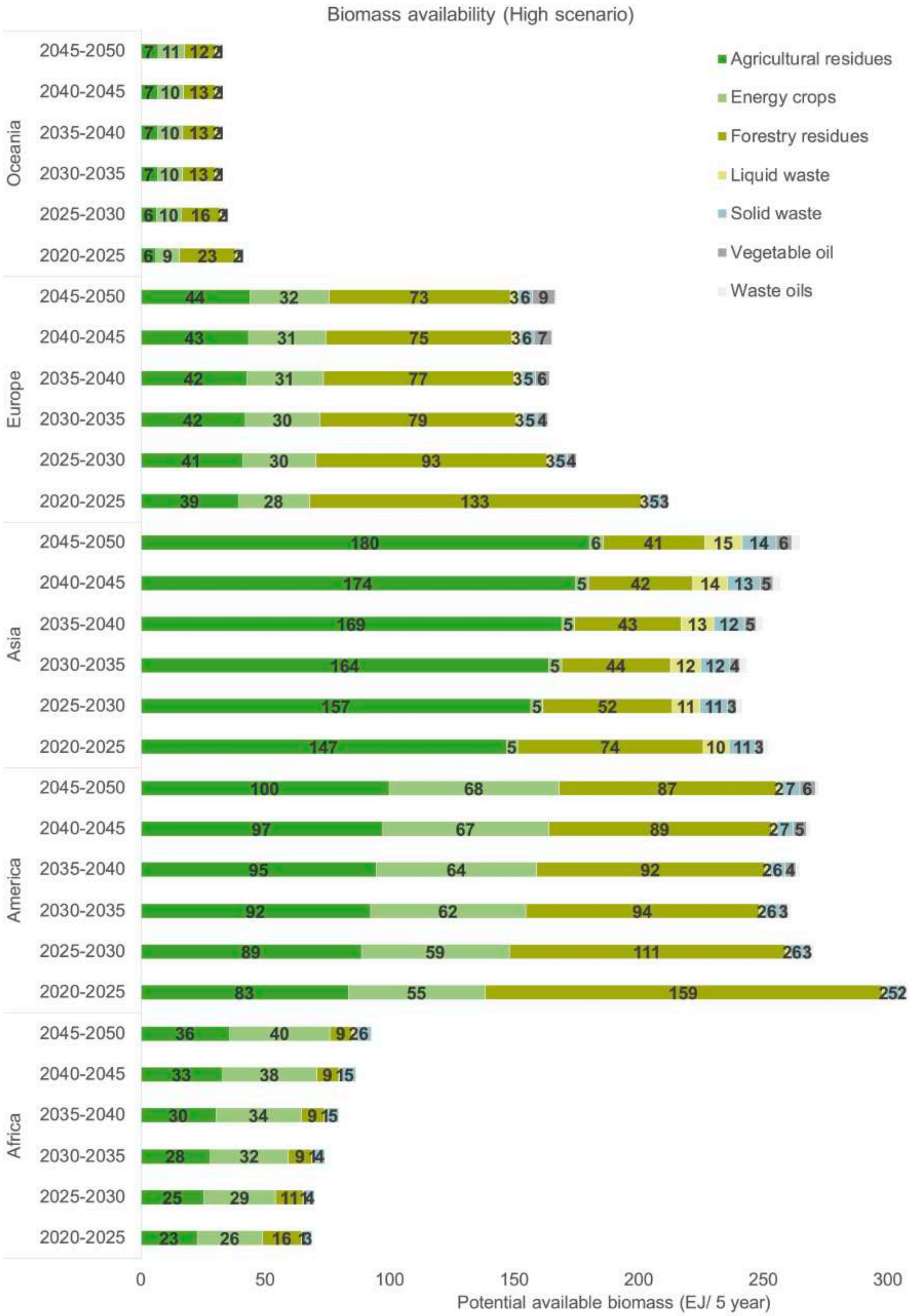

Figure 5.4: Theoretically available biomass in the High Supply (HS) scenario.

5.1.1. Oil crops

Oil crops are the main feedstocks for the production of bio-diesel. The challenge of creating drop-in biofuels is the removal of oxygen, which is included in the biomass feedstock [132]. Besides the fact that the high oxygen content of biofuels makes them unsuitable for use in the existing petroleum infrastructure, it also reduces the energy content of the fuel. Oil crops or lipids have a very high hydrogen to carbon content compared to sugars and cellulosic materials. This makes them convenient for conversion to biofuels, seeing that their high hydrogen content makes extra refining steps, in which hydrogen is added, unnecessary [132]. This is the main reason that fuels like FAME and HVO are already commercially available.

The use of vegetable oils for the production of biofuels is a highly controversial topic. Especially the use of soybean and palm oil involves high risk on ILUC. Additionally, most of these oil crops form direct competition with food chains. However, for the transition phase, it might be inescapable to make use of these feedstocks.

To estimate the future regional availability of vegetable oils, the agricultural oil-seed outlook of the Food and Agriculture Organisation of the United Nations (FAO) is used. This outlook provides in-depth projections of the regional production of vegetable oils. Domestic production of vegetable oils is discounted with imports and exports to obtain the total available amount of vegetable oil per region. The amount consumed for food purposes is deducted from the total to obtain the amount of vegetable oil available for the production of biofuels. A more in-depth visualization of this estimation is shown in Appendix B.1.

Both the low and high supply scenario use the FAO oil-seed outlook as a base. To make a projection until 2050 of the vegetable oil supply potential, different growth rates are used. Production and consumption growth rates from FAO are discounted to one net growth rate for each region. The availability is further specified per sub-region by multiplying the total with the sub-regions share of oil crop production, which is obtained from the FAO.

5.1.2. Waste oils

Gui et al. [71] defined waste oils as "oil-based substances consisting of animal and/or vegetable matter that has been used in cooking or preparation of foods and is no longer suitable for human consumption". The most common waste oils are UCO and tallow (animal fats), which today account for approximately 20% of global biodiesel production [23]. Some of the sustainability issues that are associated with the use of oil crops for fuel production, do not apply to waste oils.

Used Cooking Oil (UCO)

The disposal of UCO has become a problematic issue in most countries. UCO cannot be discharged into drainers or sewers, because this results in blockage of filters and difficulties with the water treatment systems [71]. Therefore, collecting these oils and using them for fuel production is a convenient solution.

Although there are benefits to using UCO and tallow as biofuel feedstocks, there are also some concerns. The demand for UCO experienced a rapid increase when Europe introduced the RED. The first RED was associated with the ILUC directive, placing a cap of 7% on the use of primary crops for fuel production. On the other hand, advanced feedstocks like UCO counted double, causing the demand for UCO in Europe to expand. This gave value to UCO as a commodity and caused a shortage in the domestic UCO availability in Europe. This shortage of UCO induced the rise of UCO trade flows from third world countries. Europe imported around 500.000 tons of UCO in 2018.

Loizides et al. [95] stated that there are no accurate estimates of global UCO production. This is mainly caused by the lack of reporting and the significant challenges related to estimating UCO production from oil consumption patterns [95]. Gui et al. [71] estimated that about 16.54 million tons of UCO are produced every year among the largest producing regions (China, Malaysia, the U.S., Europe, Taiwan, Canada, and Japan). He emphasized that the worldwide potential is way larger than this. Hence, the potential of UCO is considerable. However, the challenge is to find an efficient way to collect it. The development of a logistic network that can collect small amounts of UCO from many individual households is a severe challenge.

The total UCO potential is estimated by using two factors. The first factor indicates the percentage of total vegetable oil consumption that is retrievable as UCO. A significant part of the UCO is often absorbed in the food, making only a small part of it usable as UCO. This factor is also dependent on the dietary habits of the population [73]. For Europe, the values of Hillairet et al. [73] are taken. Numbers for Western Asia are assumed similar to East Europe. China is known to export significant quantities of UCO. The populations of China and the U.S. are known to consume a lot of fried food. Therefore, high retrievable UCO potentials are estimated. For the remaining regions, in the low scenario, a retrievable percentage of 10% and 15% are assumed for the low and high scenarios respectively.

A second factor indicates the percentage of the retrievable UCO that is collected. For Europe, these factors are taken from Hillairet et al. [73]. The collectible UCO potential is assumed similar for Northern America and Eastern Asia as for Western Europe. It is assumed that in Africa no logistic network for the collection of UCO will be established in the studied period. In South America, the collectible potential of Brazil and Argentina is assumed to be relatively small.

Potential growth in UCO availability over time is a combination of growing vegetable oil consumption and an improving collection system. For Europe, the growth forecast of Hillairet et al. [73] is used. For the remaining regions, the expected population growth is assumed proportional to the future UCO availability. In the low supply scenario, little action of governments in improving UCO collection systems is expected. In the high supply scenarios, proactive support of member states is assumed.

Tallow

Tallow accounts for about 7% of worldwide biodiesel production. Similar to UCO, the global availability of tallow is difficult to assess. According to a report of Biofuel Watch [29], all slaughterhouses worldwide produce around 7 million tons of tallow as a by-product, yielding approximately 5 million tons of biodiesel, which would be able to fuel around 1.7% of the global aviation industry. Taking into account that meat and dairy consumption is expected to decrease, this maximum tallow availability is not expected to grow.

Tallow can be categorized into categories 1, 2, and 3. Category 1 tallow presents a high risk for human health and is thus not suitable for use in human or animal feed chains. Category 2 tallow is derived from animals that died from other causes than slaughter for human consumption. Category 3 tallow originates from animals that are slaughtered for human consumption [17]. Only categories 1 and 2 tallow are classified under Annex IV-B of the RED II.

According to Alberici et al. [17], around 730 million liters of tallow biodiesel was produced in Europe in 2012. About 250 million of this total was category 3, the remaining tallow based biodiesel was category 1 and 2 combined. Data from the FAO is used to assess the regional production of tallow, the most recent data originates from 2014. Category 3 is not included in the available potential, seeing that this product is not included in the RED II targets and could serve higher purposes than being burned as fuel. A general percentage of 35% category 3 tallow is assumed, based on the data of Alberici et al. [17].

5.1.3. Agricultural residues

Many suggest that the most promising feedstock for the production of advanced biofuels is lignocellulosic material [20, 126]. According to Hsieh and Felby [78], the only way for biofuels to comply with the large scale of marine fuel consumption, and continue doing this in the long-term, is to produce marine biofuels from lignocellulosic residues. The main reasons for this are the sustainability and availability concerns that are related to biofuel production from oil, starch, and sugar crops [78]. Lignocellulosic biomass is abundantly available and is about five times cheaper than oily feedstocks [78]. Lignocellulosic feedstocks are woody, not edible feedstocks that consist out of lignin, cellulose, and hemicellulose [126, 142]. They can among others be used as feedstocks for HTL, Fast-Pyrolysis (FP), Gasification Fischer-Tropsch (GFT). In this thesis, lignocellulosic feedstocks are subdivided into three categories, agricultural residues, forestry residues, and energy crops. Forestry residues and energy crops are further discussed in sections 5.1.4 and 5.1.5 respectively. Agricultural residues can be divided into two categories - field residues and process residues. Field residues are produced when the crops are harvested. They consist of stubble, stalks, straw, leaves, and seed pods. Process residues result from the conversion of the crops into a usable product. These residues include husks, chaff, cobs, bagasse, molasses, and roots.

Agricultural residue availability estimations show significant discrepancies [83]. De Wit and Faaij [45] states that the most common method to determine agricultural residue supply potential is by applying two ratios on the annual country average commodity statistics. These annual average commodity statistics for the production of crops are obtained from the FAO. The first ratio is a general residue use factor. This factor entails that only part of the available residues can be used for energy purposes. A part of the residues is left on the land to maintain a healthy soil structure and enhance mineralization kinetics [46]. Both De Wit and Faaij [45] and [62] use a factor of 50%, which is relatively conservative. Some sources indicate that only 20-25 % is needed for soil maintenance. The second factor is the Residue-to-Product (RPR) ratio and is crop-specific [45]. The RPR ratio indicates the amount of residue that is produced to the harvested amount of the original crop.

Using this method to indicate residue availability is a study on its own and is already performed several times by others, all resulting in different outcomes. These different outcomes are also caused by a relatively subjective conviction of what percentage is sustainable to use. In this thesis, the global availability of different biomass types is estimated by using and comparing other in-depth literature on this topic.

Leguijt [92] performed a detailed study on the availability of biomass both on an EU and global level. They compared six studies that assessed regional biomass availability. One of the most elaborate studies used by Leguijt [92] was published by IRENA [83]. IRENA [83] made detailed supply and demand projections of various biomass feedstocks, including agricultural and forestry residues. The regions in which they determined the availability were Asia, Latin-America, Africa, Europe, North America, and OECD pacific. To further specify the availability per region, the national crop production statistics of the FAO are used as a ratio for the division of availability over the specified regions. To estimate the availability over the studied period, historical and projected annual crop production numbers of IRENA [83] are used.

5.1.4. Forestry residues

Different parts of a tree trunk are usually used for different purposes. Saw logs are used for the manufacturing of housing, furniture, and interior. Pulpwood is intended for the manufacturing of paper. Forestry residues can be classified as primary or secondary residues. Primary forestry residues are logging residues, early thinning, and extracted stumps, while secondary forestry residues are residues from the processing of wood in industry [59]. Both waste streams are convenient sources for the production of advanced biofuels.

To estimate the availability of forestry residues, domestic wood production data of the FAO is used to come up with regional shares of forestry residue availability. These shares are multiplied with the regional availability from Leguijt [92]. For forestry residues, no detailed projections were found. The study of Leguijt [92] gives two values for the sustainable potential of forestry residues in 2030 and 2050. From these numbers, the potential of forestry residues seems to stay relatively constant between 2020 and 2050. From 2030-2050 a slight decrease in the global potential availability of forestry industries is seen in the studies of Leguijt [92] and IRENA [83]. Because no further explicit regional estimations were found in the literature, a global growth/decline rate is assumed. These rates are based on linear interpolation between 2020, 2030, and 2050 values of Leguijt [92].

5.1.5. Energy crops

In general, two types of energy crops can be distinguished, conventional, and lignocellulosics [122]. Conventional energy crops are usually used to provide food for humans and animals. However, the energy crop category in this thesis only considers lignocellulosic energy crops. These are crops that consist of cellulose, hemicelluloses, and lignin (examples are miscanthus, poplar, willow, eucalyptus, and switchgrass). An advantage of these crops is that they can be cultivated with high yields. Additionally, they can grow on marginal land, which opens up the opportunity to use land containing soil conditions in which conventional energy crops cannot grow [122]. Currently, lignocellulosic energy crops are only used for heating purposes, but with the introduction of new technologies, they could also be used as a feedstock for transportation fuels.

The sustainability performance of these crops is slightly lower compared to the previously mentioned lignocellulosic residues. The reason for this is that dedicated energy crops are cultivated for energy use and are thus not considered a residue stream. Therefore, the emissions related to this process are entirely allocated to the fuel.

To project future regional energy crop potential, the method of IRENA [83] is used. They used FAO data to determine the surplus land that is available for the harvesting of energy crops. Land used for food production, non-agricultural purposes, and protected areas were already deducted. Therefore, a certain amount of surplus land per region is available for the cultivation of energy crops. In the study of IRENA [83], the surplus land is multiplied with the bioenergy crop yields. In their assessment, they used cereals as a proxy for energy crops. Seeing that they used land availability as an indicator for energy crop potential, this study uses the land area as the scaling factor to estimate values for all studied regions.

5.1.6. Solid waste

In this thesis, solid waste includes only Municipal Solid Waste (MSW). Municipal Solid Waste (MSW) entails all industrial and household garbage. At this stage, mature waste collection systems are only available in densely populated urban areas. Therefore, about 33% of global waste is disposed of by “open dump”, 22% through a landfill and about 11% is incinerated [76].

From a sustainability perspective, it would be good if this waste could be used for the production of biofuels. Incineration and landfill cause additional emissions to the life-cycle of the products. If these emissions are prevented, the environmental performance of biofuel could be tremendous. Although turning waste into fuel sounds ideal, it is also associated with some challenges. The consistency of waste streams is not constant, causing it to be difficult to provide a feedstock of constant quality and consistency. This will be further discussed in section 7.3.2, when determining the conversion yields of biomass to biofuel.

The availability of MSW for energy use is seen as solid waste potential. Only the food, paper/cardboard, and wood waste fractions of MSW were considered to have the potential for energy use. which is recommended by IRENA [83]. They used country-specific data for the amount of MSW produced per capita per year from the Intergovernmental Panel on Climate Change (IPCC). The recoverable potential is assumed to be in densely populated areas where there is a well-organized waste treatment infrastructure. Per region, shares of the population that live in urban areas are taken from Our World in Data. These factors are used as a correction to the total potential availability. Scarlat et al. [118] estimated the global potential of MSW to be between 13-30 EJ/year by 2025. These values were calculated assuming the energy content of MSW between 6-14 MJ/kg. They indicated that a best guess would be the average, using an energy content of 9 MJ/kg, which resulted in a global potential of 20 EJ for 2025. This energy content is also used in the estimation performed in this thesis. The method is described in more detail in Appendix B.1.6. Growth rates used in this estimation were based on population growth per region.

5.1.7. Liquid waste

The liquid waste category includes both animal manure and sludge from wastewater plants. Liquid waste is often used to produce biogas. However, manure and sludge could also be used as an input for HTL. Comparable to MSW, sludge is also often incinerated. Hence, using this feedstock for biofuel production and preventing incineration, causes the reduction of emissions. Animal manure causes the release of methane in the air, which is why turning it into either biogas or biofuel would be advantageous for the environment.

The regional availability of manure is estimated with livestock data from the FAO. The amount of solid manure per animal is determined and recovery rates of IRENA [83] are used to determine the recoverable potential. For sludge from wastewater, the collected wastewater volumes from AquaStat are used. Values for Africa, America, Asia, Europe, and Oceania are further divided over the sub-regions by share of the total population. To estimate the available amount of dry sludge, 0.2 dry ton of sludge per million liters of collected wastewater was assumed. Although the theoretically annual available energy potential of manure is large (around 10 EJ), the amount that can be recovered for energy use is smaller. This is mostly due to difficulties in the collection of this manure.

5.2. Competing industries

Besides the shipping industry, several other industries have potential demand for bioenergy. To determine the potential biomass availability for the production of marine biofuels, the demand for these other industries need to be evaluated. Figure 5.5 indicates the main potential users of biomass.

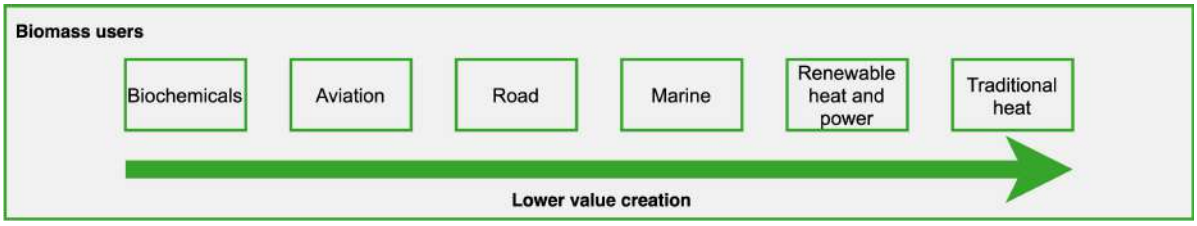

Figure 5.5: Competing users of biomass with different value creation per sector.

From figure 5.5 it becomes clear that certain sectors can create more value out of the biomass than others. This leads to these sectors having a competing advantage over the other sectors when sourcing biomass. Hence, the method shown in figure 5.1 is pessimistic, seeing that the maritime industry might have priority in using biomass over the heat and power sectors. The biochemical sector is a potential competitor and could arguably create the most value out of biomass feedstocks.

de Jong et al. [43] made a similar estimation to obtain the biomass available for the production of renewable jet fuel in Europe. He stated that the biomass supply available for the production of bio-jet fuel is mainly dependent on the biomass demand for heat, electricity, biochemicals, and biofuels. According to de Jong et al. [43], biochemicals form a relatively small part of bioenergy demand. After conversations with experts from TNO, it is recognized that the biochemical industry might be a competing user for biomass in the future, but the size of the competition of this industry is highly uncertain. It is therefore decided to leave a detailed analysis of this industry out of the scope of this thesis.

Besides excluding biochemicals, detailed analysis of the feedstock use of competing industries is outside the scope of this study. Assumptions are made based on other studies to estimate the availability of the different feedstocks in every studied region for the production of marine biofuel. To cope with the uncertainty of future biomass demand from these sectors, de Jong et al. [43] used a low and a high competition scenario. In this analysis a similar approach is used, in which a low and a high competition scenario are developed. In the remainder of this section, the results indicated in figures 5.6 and 5.7 will be further elaborated upon. Supplementary information regarding the determination of competing biomass use are given in Appendix B.2. The low competing scenario is used to determine the high availability scenario and the high competing scenario corresponds to the low availability scenario.

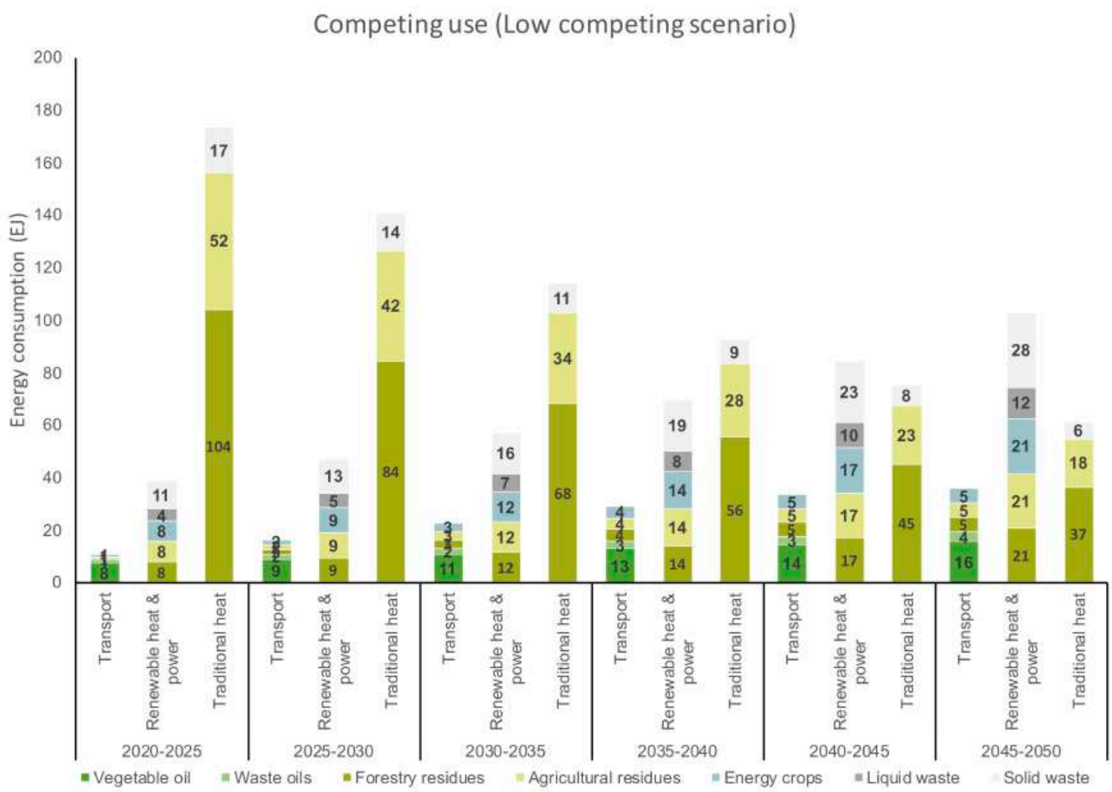

Figure 5.6: Competing use of biomass in low competing scenario.

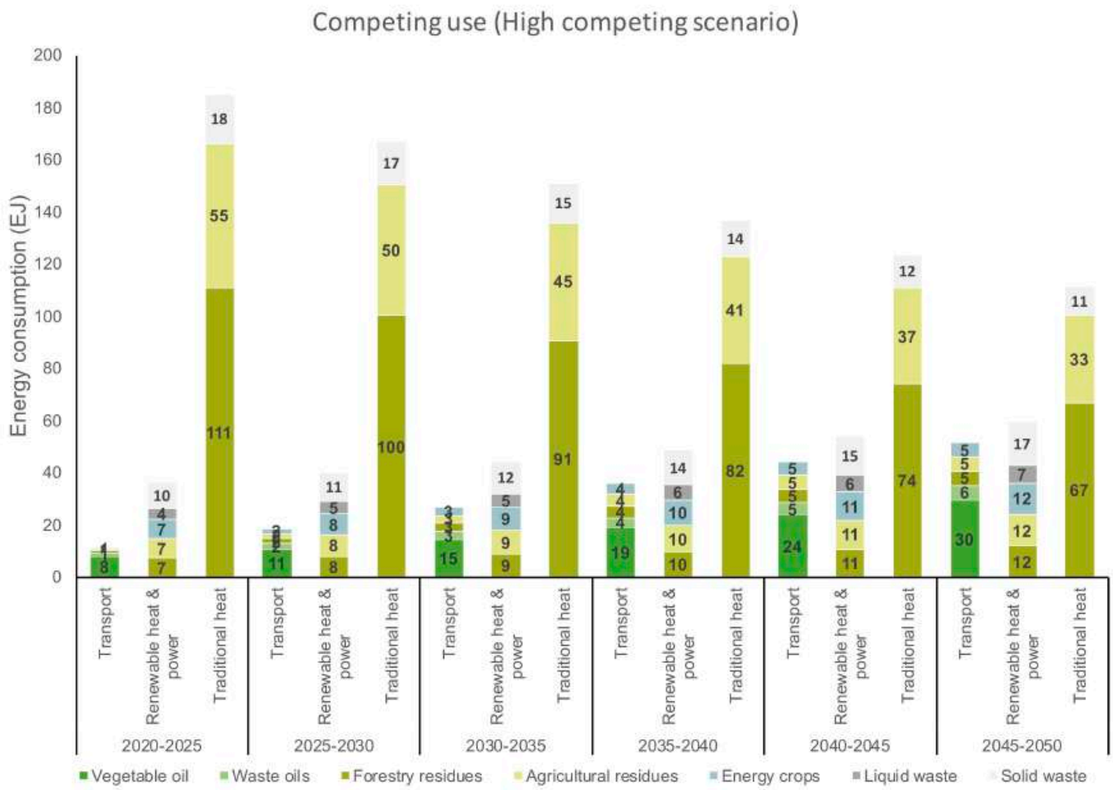

Figure 5.7: Competing use of biomass in high competing scenario.

5.2.1. Renewable heat and electricity

The production of heat and electricity can be either done in dedicated heat or power plants or Combined Heat & Power (CHP) plants. Two types of bio-heat can be distinguished. Renewable heat from power plants is used to heat residential and commercial establishments. Direct heating includes renewables that are not used for renewable heat from power plants, electricity, or transport. The most significant part of direct heating is used for heating and cooking. The traditional use of biomass for heating and cooking is further discussed in section 5.2.2.

Kraan [87] indicated that in 2015, the demand for renewable heat in Europe was about 2,6 EJ. The global demand for total bio-heating has been relatively stable over the last decade, demanding about 40 EJ of biomass. This figure also included direct heating (traditional biomass use). The renewable heat produced in Europe accounts for 84% of the renewable heat produced globally. The main feedstocks used for bio-heat production are wood chips, wood pellets, and waste [131].

Current data of the International Energy Association (IEA) is used to assess the amount of biomass used for the generation of heat and power per region. The IEA structured their data into heat only, power only and CHP plants. The feedstock categories that they included are municipal waste, industrial waste, solid biofuels, and bio-gas. Bio-gas is in this case mostly produced from manure. Municipal waste and industrial waste are in this thesis captured within the solid waste category. Solid biofuels are distributed over all lignocellulosic categories (agricultural residues, forestry residues, and energy crops). Because no further sub-categorization was provided by the IEA, an even split between these categories is assumed. A part of this will also include fuelwood, which is not included as a potential feedstock for advanced biofuels in this thesis and is therefore deducted.

5.2.2. Traditional heat

It is important to note the difference between renewable heat (modern heat), which was discussed in the previous section, and direct heat (traditional use of biomass). Traditional use of biomass includes the use of charcoal and firewood for cooking and heating, mostly in open stoves Fritsche et al. [66]. This traditional use of biomass is still common practice, especially in developing countries. According to the WBA, around 40 EJ/year is still used for traditional biomass use. Comparing this to the use of biomass for renewable heat, the annual energy consumption of traditional biomass use is around 40 times higher.

Seeing that the traditional use of biomass for cooking and heating is extremely inefficient, it is attempted to decrease it. Besides the fact that traditional biomass use is inefficient, it also causes deforestation and health issues [122]. Therefore, it is expected that the use of traditional biomass for heating and cooking will be slowly replaced by renewable heating [83]. Because renewable heat is significantly more efficient, this decreases the amount of biomass that is required. In the low availability scenario, a slow replacement of traditional biomass use is assumed. In the high availability scenario, a rapid decrease of traditional biomass use is assumed.

Data on the use of specific feedstocks for traditional heat was not available. However, it is known that most traditional heat is generated in pellet stoves and boilers. IRENA [83] indicated that "the majority of biomass used for heating is solid fuels, including wood logs and twigs, wood chips, and sawmill residues. In some countries, especially in rural areas, agricultural residues, such as straw, are also used." Looking at the current use of forestry and agricultural products indicated by Leguijt [92], it is assumed that around 30% of traditional biomass demand is covered by forestry residues. Agricultural by-products and MSW are both assumed to contribute around 10%. The remaining 50% is assumed to be covered by charcoal and fuel-wood.

5.2.3. Aviation, road, and rail

The final user of bioenergy is the transportation sector. As indicated in figure 5.5, the transportation sector can be divided into aviation, road & rail, and marine. In the market analysis of Kraan [87], the demand for biofuels was not categorized into these different modes of transport. de Jong et al. [43] used the RED II targets to predict future demand for biofuels in the road and rail sector. They included constraints on these targets in their model and did not analyze noncompliance scenarios [43].

In this study, data from Organisation for Economic Co-operation and Development (OECD) statistics are used to predict future demand for bio-diesel until 2028. This data was not specified per sector. The demand for biofuels from the marine and aviation industry is at this stage negligible. Therefore, the biodiesel consumption data from the OECD is contributed to the road sector. No specific data was known for the use of waste oils for the production of biodiesel. Figure 2.1 indicate that approximately 20% of the global produced biofuels are made from waste oils, the remaining 80% is produced from vegetable oils. The RED II is a strong incentive for Europe to use waste oils. It is assumed that 30% of the biodiesel consumed in Europe is made from waste oil. Countries like the UK, Finland, the Netherlands, and Ireland fulfill half their renewable targets with waste oil-based fuels. This is caused by regulations stimulating the use of these fuels. For the USA, 5% waste oil-based biodiesel is assumed. This number is based on data from the U.S. Energy Information Administration (EIA). The remaining regions are assumed to only use vegetable oils.

The increase in the use of biofuels for the road sector is among others dependent on its electrification rate. When the transition to electric vehicles happens rapidly, more biodiesel could be available for the marine and aviation industries. The OECD estimated the use of biodiesel in the road sector to remain at current levels until 2028. However, IRENA [83] estimated an increase of biofuel usage by all transport sectors of 9.7 % per year. The FAO estimates biodiesel consumption to grow by around 2 % between 2020 and 2025. These different outlooks are used for the low and high availability scenarios. In the low availability scenario, the road sector is expected to increase its biodiesel use by 10% per year, which is significant but implies an upper bound. For the high availability scenario, the use of biodiesel by the road sector is increased by 2 % per year.

IEA's sustainable development scenario is used to estimate the future use of biomass by the aviation sector. This scenario states that 10% of total aviation bunkers will be bio-based by 2030. In 2040, the share of bio-based fuels in the aviation fuel mix will be 20%. This corresponds to 37 and 75 billion liters of bio-jet fuel. According to de Jong et al. [43], the largest part of these volumes will be fulfilled using Alcohol-to-Jet (ATJ) and Hydrotreated Esters and Fatty Acids (HEFA). Increasing use of ATJ, induces competition for lignocellulosic material. The increasing use of HEFA in the aviation sector causes competition for oily feedstocks. de Jong et al. [43] predicts only about 20% of the bio-jet fuel to be produced via fast pyrolysis, HTL and Fischer-Tropsch (FT) by 2030. However, together with ATJ, the aviation sector is expected to cause significant competition for the use of biomass by the maritime industry.

Yields on an energy basis for renewable jet fuel production via the mentioned conversion pathways range from 7% for upgraded pyrolysis oil to 54% for HEFA [43]. For renewable jet fuel production, only the light fractions can be used. According to an old publication of the RIVM, the USA is responsible for approximately 50% of aviation bunker sales. Aviation energy demand ratios from the RIVM are used to divide the total biofuel consumption over the selected regions.

5.3. Available biomass for marine

In the previous two sections, the regionally available amount of biomass and the use of competing industries is estimated. Following the method stated in figure 5.1, this data can be used to estimate the amount of biomass available for the production of marine biofuels. Subtracting the competing biomass users from the regional theoretical biomass potential yields the remaining availability depicted in figures 5.9 and 5.10 for the low and high availability scenarios respectively.

5.3.1. Assumptions

Because the determination of the global biomass that will be available for the shipping industry until 2050 is an enormous task, in which a lot of uncertainty is embedded, two significant assumptions are made.

- Current imports and exports of feedstocks are not taken into account (except for vegetable oils).
- When specific data was not available, substantiated estimations were performed.

Firstly, when subtracting competing users from domestic biomass availability, some feedstock potential turned out to be negative in certain areas. This is due to the neglecting of current trade flows from wood pellets. The areas in which this occurred were set to zero potential. This leads to a slight overestimation of the amount of feedstock currently available.

Secondly, due to the significant required amount of data, on several occasions values needed to be estimated. This entails a series of assumptions, which causes some uncertainty in the availability results. It is attempted to gain insight into the level of uncertainty in the next section, which will reflect on the results.

5.3.2. Reflection on the availability results

To validate whether the estimated availability is in a realistic range, the results are compared with the literature. Some studies that assessed the potential biomass availability on a global level per region were IRENA [83], Daioglou et al. [38], Smeets et al. [122] and Leguijt [92]. Elbersen et al. [59] also assessed the availability of biomass but performed his analysis only for Europe.

IRENA [83] and Leguijt [92] already made a comparison with other literature outcomes and they discovered a broad range in predictions of biomass availability. When looking further ahead in time, this uncertainty increases. This is especially true for agricultural residues, forestry residues, and energy crops. IRENA [83] discovered a spread in predicted availability for 2030 of 80 EJ/year and 150 EJ/year for energy crops and agricultural residues respectively. By 2050, the spreads were found to be between 50 EJ/year, 500 EJ/year, and 200 EJ/year for energy crops, agricultural residues, and forestry products respectively. Bioenergy [28] also indicated that technical biomass potentials in the literature can reach as high as 1500 EJ/year by 2050. They add to this that when sustainability criteria are taken into consideration, estimates are generally between 200-500 EJ/year. From this, agricultural, forestry and municipal residues account for 50-150 EJ/year. The rest is filled with lignocellulosic energy crops.

A visualization of the availability results used in this thesis with other literature sources is given in figure 5.8. When looking at this figure a couple of side notes need to be considered. Firstly, the biomass potential in this study covers all discussed feedstock categories, whereas the results of CE Delft only cover agricultural and forestry residues. The studies of Hoogwijk and Graus [75] and Smeets et al. [123], cover agricultural residues, forestry residues and dedicated lignocellulosic energy crops. Additionally, Daioglou et al. [38] and Smeets et al. [123] used a different categorization for the used regions. They included Russia in the Asian category, while the other studies included Russia in the European category. Russia's biomass potential is significant, which explains the difference in biomass distribution between Daioglou et al. [38] and other studies. The study of Smeets et al. [123] stands out due to its prediction of enormous biomass availability. The significant biomass availability shown by Smeets et al. [123] is mainly due to the potential of energy crops. Energy crops can be grown on marginal land. How much marginal land can be used for the cultivation of energy crops can only be based on subjective arguments. Smeets et al. [123] added some nuance to the determined biomass availability by stating that "the realization of these (technical) potentials requires a significant increase in the efficiency with which food is produced.".

It can be concluded that predictions of future biomass availability are very uncertain. Leguijt [92] assigns this uncertainty to cultivation productivity, the potential amount of land available for the cultivation of energy crops, forestry management methods, and the need for biodiversity. Although the biomass availability predictions vary across various literature sources, this thesis attempted to combine insights and capture part of the uncertainty in two scenarios. The largest part of the results is based on the study of IRENA [83], which becomes clear from figure 5.8.

The found theoretical availability of biomass is enormous. The total estimated biomass availability is 108 EJ/year and 185 EJ/year in 2020 for the low and high scenarios respectively. However, when compared to the other assessments, the used availability is conservative. The sustainable potential slightly drops till 2030 because the use of forestry residues for traditional heat is discouraged [92]. Till 2050 the global biomass potential experiences a rise due to the expected crop production growth rates mentioned by IRENA [83].

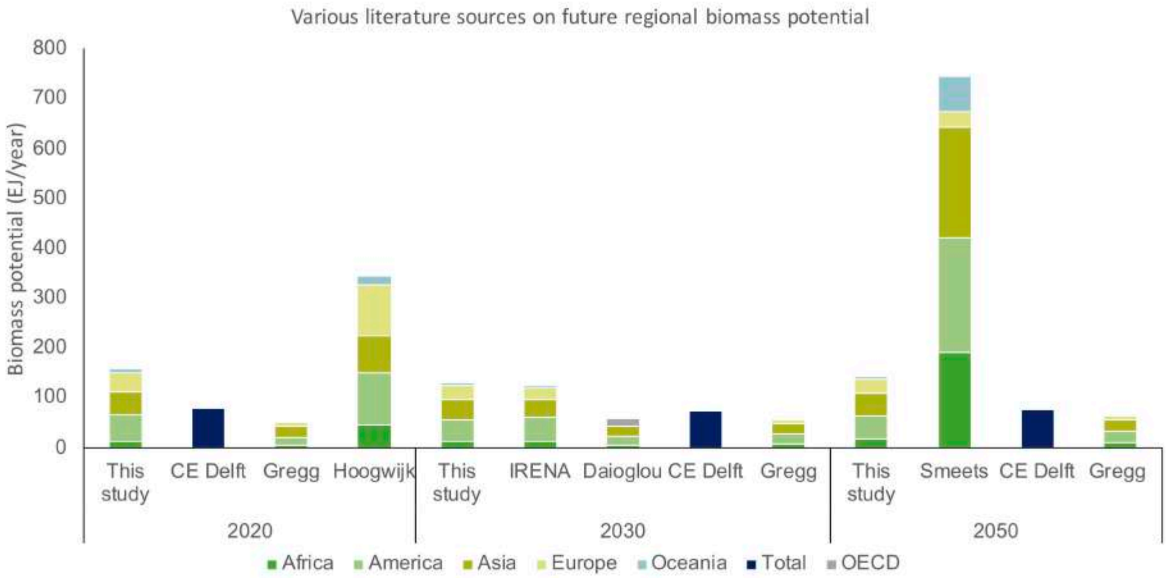

Figure 5.8: Comparison of various literature sources on future biomass supply [38, 69, 75, 83, 92, 123].

In all mentioned studies, oil crops were not included in the availability analysis. Due to the previously mentioned assumptions, the sustainable biomass potential for vegetable oils might be slightly overestimated. When subtracting the biodiesel use data of the OECD and the expected growth in biodiesel demand from the aviation sector from the current supply of vegetable and waste oils indicated by the FAO, it seems that there will not be enough supply of these feedstocks. In the low availability scenario, a shortage of oil crops of around 3 EJ/year is expected, which is significant.

From the net availability results, it appears that to fulfill the expected oil crop demand from the transport sector, the production of vegetable oils needs to be significantly increased. When looking at the historical course of vegetable oil production, the produced amount of vegetable oils doubled between 2002 and 2018 [130]. However, it could be argued whether increasing oil crop cultivation indistinctly leads to high ILUC and thus overshoots its mark. Additionally, human vegetable oil consumption also shows a steadily increasing trend. This awareness is important and only increases the need for the development of new conversion pathways that make use of residue streams.

When looking at the other competing users, now and in the future, an increase in biomass use was found for all sectors except for traditional biomass use. It is expected that biomass will therefore be more efficiently used, which also increases sustainable availability.

Comparing the total available amount of biomass to the yearly energy use of the shipping sector, which is around 12 EJ, there seems to be a lot of unused potentials. However, the difficulty lies in the collection of biomass feedstocks, seeing that they have a low energy density and are spread out over enormous areas of land. Consequently, in theory, there might be significant amounts of biomass, but in practice, most of it could be difficult to access. Also, the technologies that make use of these lignocellulosic feedstocks still have to become commercially available.

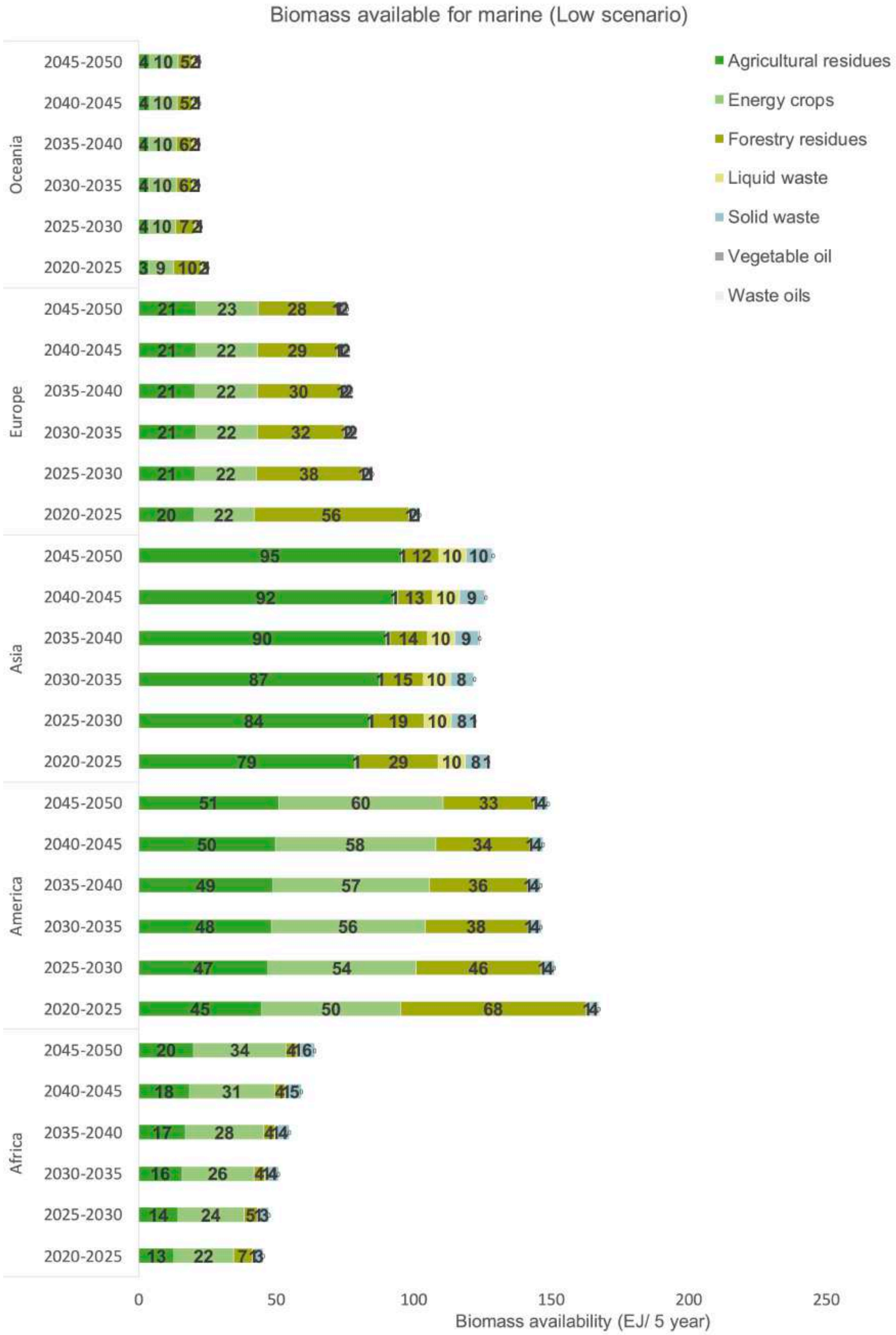

Figure 5.9: Theoretically available amount of biomass after deduction of competing users, low availability scenario.

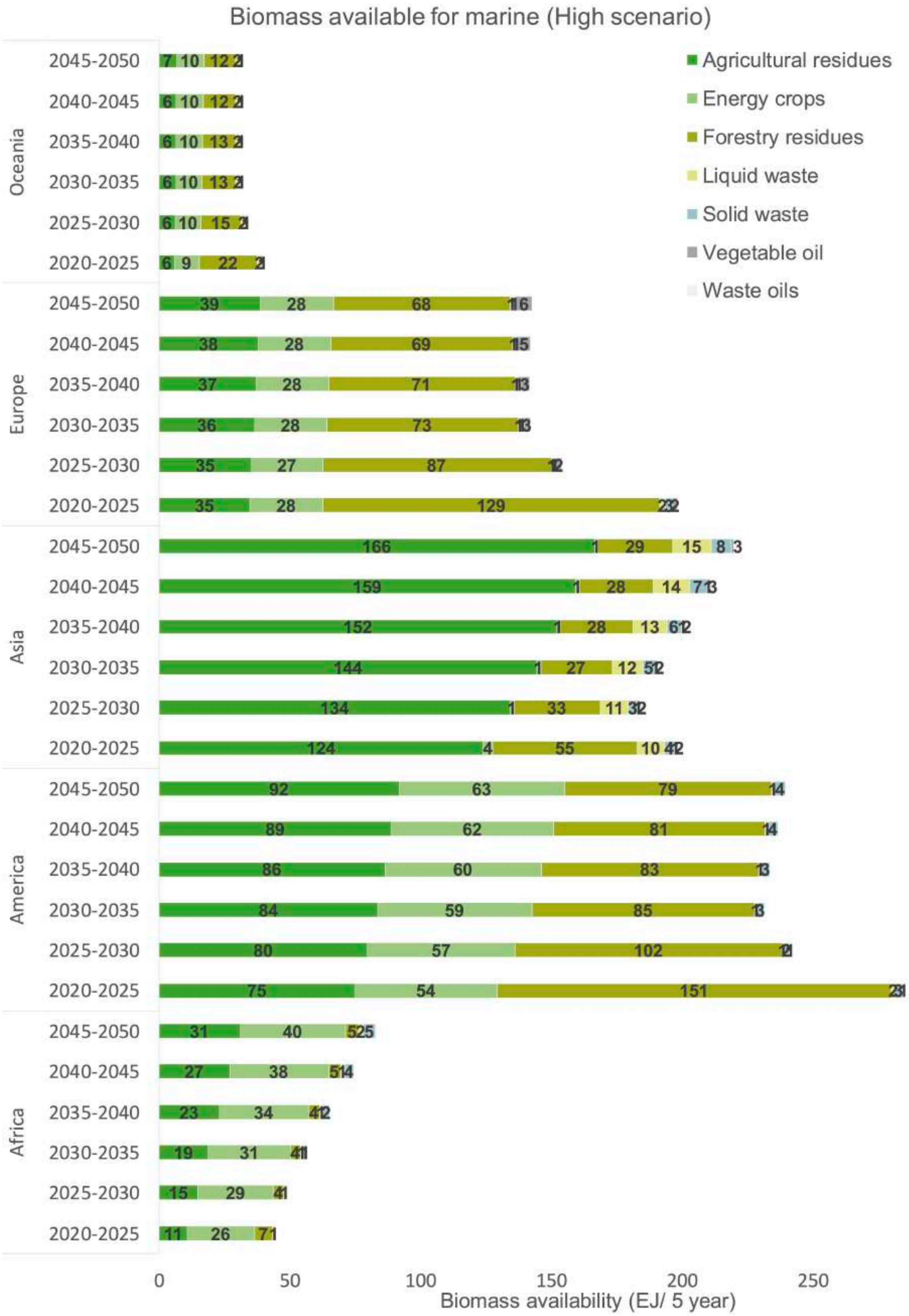

Figure 5.10: Theoretically available amount of biomass after deduction of competing users, high availability scenario.

6
Marine biofuel demand

In the previous chapter, different biomass supply scenarios were established. This chapter focuses on the demand side of the marine biofuel supply chain. The following sub-research question is answered.

What will be the impact of different future regulatory scenarios on marine biofuel demand?

To achieve this, the following method is used.

1. **Determine the regional marine energy demand**
2. **Determine the future share of biofuel in the marine fuel mix**

In section 6.1, the global energy consumption of the shipping industry is determined. Furthermore, global demand is used to estimate regional demand. In section 6.2, the share of biofuels in the future marine fuel mix is projected into different scenarios.

6.1. Marine energy demand

In general, there are two ways to assess bunker consumption, top-down and bottom-up [99, 124]. The top-down method requires the collection of data from port authorities, bunker firms, refineries, trading, and storing companies [106]. The bottom-up method estimates the consumption of the world fleet by analyzing voyage distance, fuel consumption, and other vessel characteristics. In his study, Mazraati [99] explains the challenges in the gathering and processing of bunker data. Using a bottom-up approach could lead to a valid estimation for bunker consumption, but it requires lots of data, and it is difficult to specify regional bunker consumption [99]. A top-down approach requires the constant gathering of reliable data, which is difficult because of alternating definitions in the categorizing of data between nations.

The IMO publishes a periodic study on GHG emissions caused by shipping [124]. The prospects of future GHG emissions developed in this report are based on in-depth estimations of the marine bunker consumption. The IMO performed both a top-down and a bottom-up analysis and compared them to each other.

In the top-down approach, the IMO uses data from the IEA. The IMO reviews the data from the IEA and indicates the same causes for data inconsistencies as Mazraati [99]. The two main causes are inconsistencies in definitions and non-homogeneous data quality. Additionally, only a handful of bunker ports, representing about 20% of the global bunker sales, publish their fuel sales data [8].

For the bottom-up method, the IMO has made an in-depth activity-based inventory method involving designated models for determining fuel consumption of the world fleet. The basis of this analysis is the combination of Automatic Identification System (AIS) data, technical data, and data from studied literature [124]. To obtain high-quality results with this approach, a lot of reliable data is required. The IMO states that the AIS data has become significantly more reliable.

Comparing both approaches of the IMO, the bottom-up approach leads to significantly higher values than the top-down approach. The IMO states that the difference between the two methods became smaller when the quality of AIS data was improved. From the top-down approach, the export-import discrepancy was indicated as the largest source of uncertainty. For the bottom-up approach, the discrepancy between the number of ships registered as in-service and the number of ships observed in AIS, is seen as the main reason for uncertainty. Delft [48] performed quality assurance and found a confidence interval between -17% and +5% for the 2012 bunker consumption data from the IMO.

It can be concluded that there is some uncertainty in bunker statistics. However, by applying both the top-down and bottom-up method, and analyzing the uncertainties through strict quality control, the IMO has painted a clear image of the range in which total annual bunker consumption can be quantified. The main driver of marine bunker demand is the growth of worldwide trade, which in turn is driven by growth in worldwide GDP [51]. If worldwide GDP rises, the world population has more purchasing power, leading to an increase in trade [124]. According to an energy outlook of the OPEC, worldwide trade growth is expected to cause a 25% rise in primary global energy demand until 2040 [110]. This indicates that the energy demand for the propulsion of ships also increases over time. Pelkmans [114] expects the increase in global trade to cause a doubling in marine fuel demand by 2030. However, besides GDP also, other drivers are relevant for determining bunker demand. In outlooks of Delft [48] and Smith et al. [124], it is indicated that factors like increasing efficiency of ship designs, the composition of the world fleet, and new regulations might decrease fuel consumption.

In the detailed analysis of the IMO, 16 scenarios were studied. These scenarios are based on socioeconomic, energy, and policy drivers, evaluated by the IMO [124]. For this thesis, three scenarios are used, shown in figure 6.1. The used demand scenarios from the IMO are given in Appendix C. Each scenario combines a Representive Concentration Pathways (RCP) and a Shared Socioeconomic Pathways (SSP) scenario with an expected level of efficiency improvement. For a more detailed description of the chosen scenarios is referred to Appendix C.

To locate the marine energy demand, the most significant bunker hot-spots for every studied region need to be considered. Like states earlier, only Singapore and Rotterdam publish their bunker sales, which is about 20% of total global maritime bunker sales. According to Vilhelmsen et al. [137], where ships refuel is mainly affected by routing and scheduling decisions. Oh and Karimi [111] indicated that monitoring fuel prices mainly influences refueling decisions. Ship operators choose to refuel at the cheapest bunker hub, which is on their route. However, Raucci [116] states that "maritime trade routes are a function of obligatory points of passage, which are strategic locations of physical constraints (coasts, winds, marine currents, depth, reefs, ice) and political borders". He also indicates that it is unlikely for these maritime trade routes to change in the future. On top of the relatively fixed trade routes, there is only a handful of ports that dominate bunker sales due to their strategic position [137]. Raucci [116] calculated shares of fuel sales based on historical data from the IEA. The fuel shares per region from Raucci [116] are assigned to the most significant bunker ports in each region. For every region in the scope of this thesis, at least one port is chosen, shown on the map in figure 6.2. For some regions, multiple ports are chosen, seeing their significant contribution to bunker sales. The bunker share ratios of Raucci [116] are assigned to the chosen bunker ports to estimate the bunker

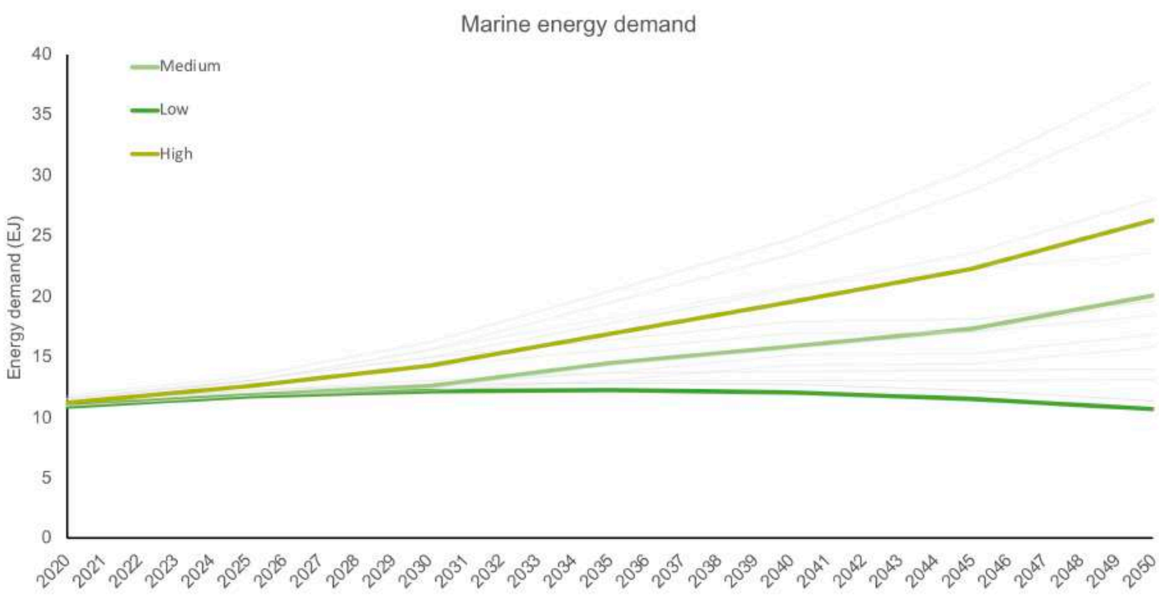

Figure 6.1: Marine energy demand scenarios considered in this thesis [124].

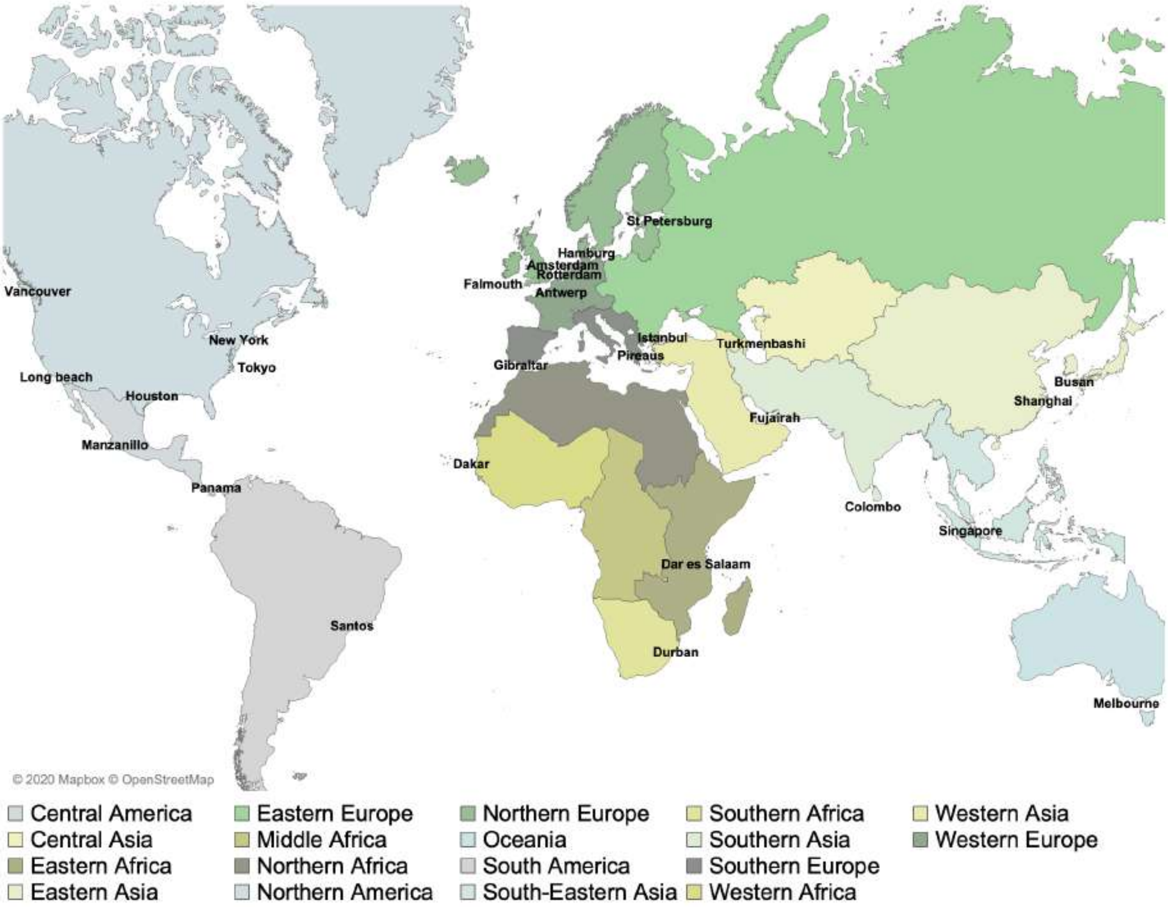

Figure 6.2: Bunker hubs considered in this thesis.

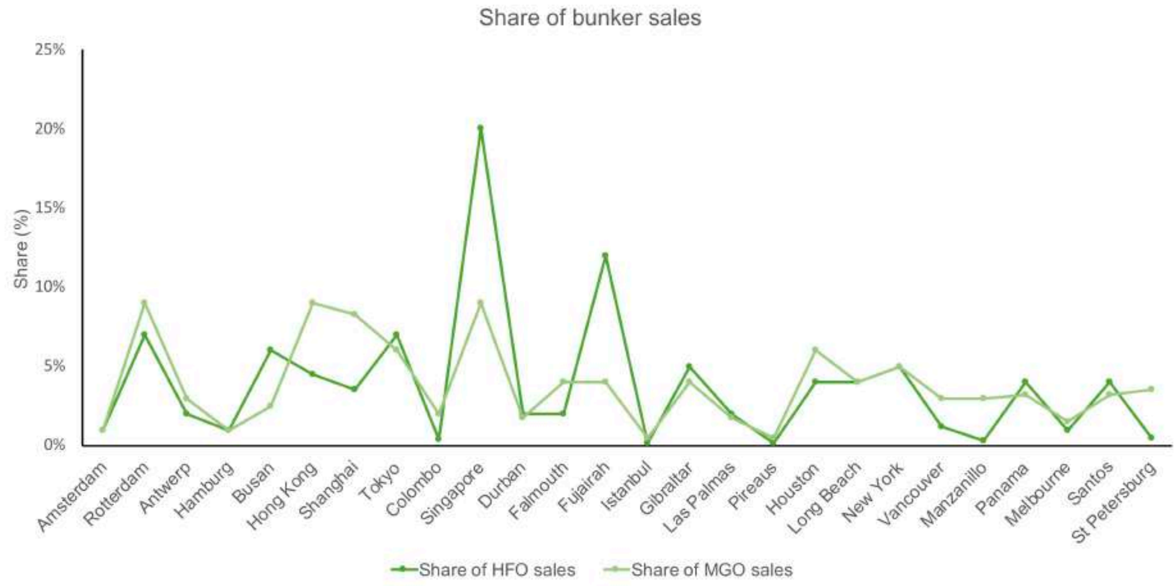

Figure 6.3: Assumed shares of bunker hubs in total bunker sales. Partly based on data from Raucci [116].

sales in that port, shown in figure 6.3. It should be recognized that the bunker volumes of the chosen ports are overestimated. However, the selected ports should be seen as nodes inside the chosen regions which represent the total bunker demand of that region.

Combining the bunker sale shares from figure 6.3 and the absolute bunker volumes from figure 6.1 results in three scenarios representing the energy demand in the selected ports. This induces the task of estimating what the future share of biofuels will be in this fuel mix.

6.2. Marine biofuel demand

Determining the demand for marine biofuel is complex. Many drivers could cause a regional uptake of marine biofuel. However, the most important driver for the possible implementation of biofuels in the maritime industry are the regulatory incentives. At this stage, no regulations that limit GHG emissions in shipping exist. However, in the future, there is a probability that such regulations will be implemented, either on an international or on a regional level. Due to this uncertainty, three scenarios are developed, which are discussed in the following subsections.

6.2.1. Europe

Europe is a global forerunner on regulating climate change. With the new RED II implementation, which was explained in section 1.3, new incentives exist for the use of alternative fuels. However, the RED II targets do not explicitly include shipping. Member-states have the freedom to decide which measures to implement, as long as the European targets are achieved. This means that member-states can decide whether to include the shipping industry in their policies. The Netherlands, where significant ports like Amsterdam and Rotterdam are situated, has a significant share of the total volume that is bunkered by ships in Europe. Currently, there is an incentive for the shipping industry to bunker biofuels in the Netherlands, due to the opt-in system. The maritime industry can contribute to reaching the RED II target by selling emission tickets to the road sector. To stimulate the use of renewable fuels in the shipping sector, the Dutch government included an additional multiplier, which increases the number of emission tickets that are obtained if alternative fuels are bunkered by the shipping sector.

Recently, a new initiative was launched by the European Commission, called FeulEU Maritime [34]. This initiative is part of the European Green Deal and included several policy options that are focused on the maritime industry. These policy options include:

1. “Support measures aiming at boosting market uptake of sustainable alternative fuels”
2. “Prescriptive requirements on blending/definition of the share of sustainable alternative fuels and/or

shore- side electricity to be used by ships in operation and at berth”

3. “Goal-based performance requirements on the carbon-intensity of energy used in marine operations and at berth, no prescribing the type of fuels to be used.”

The latter two describe a method for prescribing the use of sustainable alternative fuels. This is used as a basis for the European scenario. As such, the economic and environmental effects of such regulations can be analyzed.

In the “Europe” scenario, all ports that are situated in Europe are included in their national renewable energy target. The National Renewable Energy Action Plans (NREAP)’s describe how each member state plans to reach their individual renewable energy target. The 2020 targets for renewable fuels in the transport mix was 10%. The RED II sets a target of 14% of the transport mix to be biofuels by 2030. Taking into account double counting, this percentage might come down to about 7%, if only Annex IV-A and B feedstocks are used. However, for the purpose of this thesis, a fixed share of 14% renewables is used, without considering double counting. The reason for this is the existence of separate emission targets in most member states, which induces the need for additional emission reductions either way. No EU target after 2030 is yet specified, therefore, it is assumed that the reduction targets will continue with the same linear trend (figure 6.4).

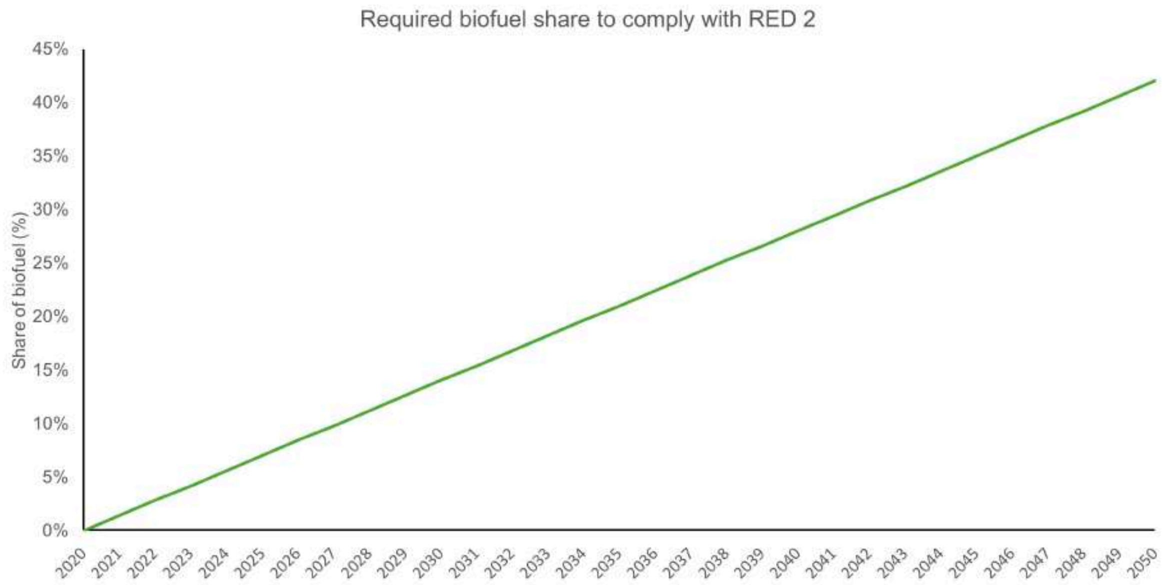

Figure 6.4: Required biofuel share to comply with the RED II.

These yearly targets can be calculated to a share per studied time period of 5 years. These admixture rates are shown in table 6.1.

Table 6.1: Shares to comply with the RED II targets.

	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Amsterdam	4%	11%	18%	25%	32%	39%
Antwerp	4%	11%	18%	25%	32%	39%
Falmouth	4%	11%	18%	25%	32%	39%
Gibraltar	4%	11%	18%	25%	32%	39%
Hamburg	4%	11%	18%	25%	32%	39%
Las Palmas	4%	11%	18%	25%	32%	39%
Pireaus	4%	11%	18%	25%	32%	39%
Rotterdam	4%	11%	18%	25%	32%	39%
St Petersburg	4%	11%	18%	25%	32%	39%

6.2.2. Most likely

Except for Europe, some other parts of the world are also active in setting up new incentives for the use of alternative sustainable fuels. In the USA, a similar system as Europe's Emission Cap and Trade System (ECTS) system is used. This Renewable Fuel Standard (RFS) system uses so-called Renewavble Identification Number (RIN) units for their cap and trade system. Analogous to the cap and trade system used in Europe, shipping is not included in the American policy.

This most likely scenario expects the most progressive countries to adopt regulations that will stimulate the uptake of renewable fuels in the shipping industry. These countries include the Netherlands, Germany, the UK, the USA, and Canada. Scandinavia is also a frontrunner when it comes to renewable fuels. However, bunker volumes in Scandinavia are fairly small, which is why no Scandinavian port was selected in this thesis. This "most likely" scenario studies the situation in which the mentioned countries include shipping into their national renewable energy targets from 2020 on-wards.

The RFS, enforced in the USA, strives to reach around 36 billion gallons of renewable fuel in their fuel mix by 2022. Within the USA, California has its targets for sustainable fuels in the transport sector, called the California low carbon fuel standard. This standard aims to reduce GHG emissions by 40% compared to 1990 levels. However, for the RFS only a short term target was found as an absolute volume of renewable fuel. No long term targets were included, making it difficult to assess what would happen if shipping would be included in this fuel standard.

Another ticketing trade system is currently running in British Columbia, called the Low Carbon Fuel Requirement (LCFS). This standard strives to reach an 80% reduction in GHG emissions by 2050 compared with 2007. Hence, if shipping would be included in these targets, a significant share of renewable fuel is required to reach these targets.

It is difficult to say which percentage of renewable fuel in the total fuel mix of each port can be expected. Therefore, it is assumed that all ports in the mentioned front-runner countries comply with the RED II targets. The associated shares of biofuel per port are shown in table 6.2.

Table 6.2: Biofuel shares used in the Most-Likely scenarios.

	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Amsterdam	4%	11%	18%	25%	32%	39%
Hamburg	4%	11%	18%	25%	32%	39%
Rotterdam	4%	11%	18%	25%	32%	39%
Falmouth	4%	11%	18%	25%	32%	39%
Houston	4%	11%	18%	25%	32%	39%
Long beach	4%	11%	18%	25%	32%	39%
New York	4%	11%	18%	25%	32%	39%
Vancouver	4%	11%	18%	25%	32%	39%

6.2.3. World

Because the shipping sector is a global industry, many argue that the use of alternative fuels should be regulated on an international level by the IMO. The main argument for this is carbon leakage. Carbon leakage is also mentioned as a significant barrier by the EU. Carbon leakage could occur when a level playing field is disturbed by the implementation of regional regulations. In contrast to other transport modes, the bunker frequency of seagoing ships is extremely low. Additionally, bunker expenses hold a significant share of a ships operational expenses. This causes the decision of where and when to bunker to be more strategical compared to other transport modes. When regional regulations cause bunker prices to go up due to mandatory blending prescriptions, vessels might decide to bunker outside the regulated regions.

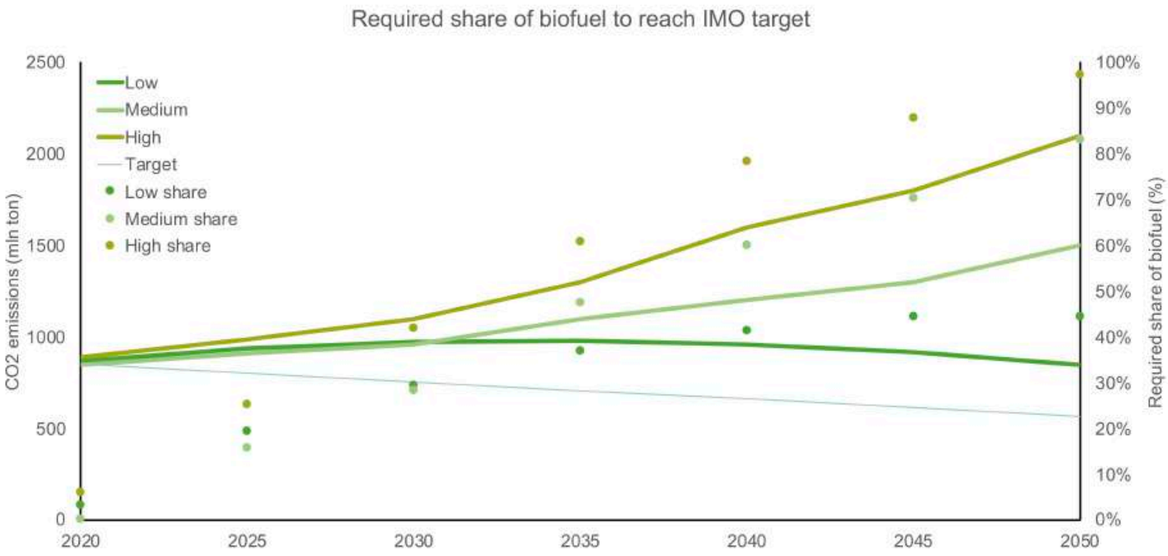

Figure 6.5: Various energy demand scenarios and consequent biofuel shares to reach the IMO target of 2050.

The "world" scenario outlines a situation in which an international mandate is implemented by the IMO. This entails that all ports in the scope of this thesis are forced to include biofuels in their fuel mix. The share of biofuels in this fuel mix is set to compliance with IMO's targets. Like mentioned earlier, the IMO set a target to reduce GHG emissions with 50% by 2050, compared to 2008 levels. Using this explicit requirement, the total required share of biofuels needed to reach this target can be estimated. This is done according to a method of Grijpma et al. [70], who used linear interpolation and an assumed GHG reduction factor of 75% for the use of biofuels. This method leads to the required shares to comply with the IMO target, depicted in figure 6.5.

The target shown in figure 6.5 can be translated to the admixture rates per studied time period visualized in table 6.3.

Table 6.3: Required shares of biofuel to be on track with the IMO target for 2050 [124].

	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Low	13%	25%	34%	40%	43%	44%
Medium	9%	23%	40%	55%	66%	78%
High	18%	35%	53%	71%	84%	94%

6.3. Demand scenarios

Judging from the previous two sections, uncertainty exists in both the future energy demand from shipping and the share of biofuel in the global marine fuel mix. To capture this uncertainty, nine biofuel demand scenarios are studied, shown in figure 6.6.

	Low demand	Baseline	High demand
Europe	• Blending requirement to reach RED 2 targets	• Blending requirement to reach RED 2 targets	• Blending requirement to reach RED 2 targets
Most likely	• Blending requirement to reach targets in frontrunner areas	• Blending requirement to reach targets in frontrunner areas	• Blending requirement to reach targets in frontrunner areas
World	• Blending requirement to reach IMO targets	• Blending requirement to reach IMO targets	• Blending requirement to reach IMO targets

Figure 6.6: Combination of the absolute energy demand scenarios and the share of biofuels scenarios, lead to 9 demand scenarios.

These scenarios form a combination between the uncertainty in future energy demand by the shipping industry and the future share of biofuels in that mix.

7

Techno-eco-environmental parameters

In chapter 4, an optimization model was developed to simulate the future marine biofuel supply chain. This chapter expands on this model by answering the following sub research question.

What are the economic, environmental and technological parameters that are required for the strategic supply chain optimization?

The model parameters that will be used for the scenario analysis can be categorized into economic, environmental, and technological parameters. Sections 7.1 and 7.2 evaluate the economic and environmental parameters respectively. Section 7.3 provides information about the technical parameters that are related to the biofuel pathways.

7.1. Economic parameters

Costs that are related to setting up and operating a biofuel supply chain can be categorized into different elements. In this thesis, the costs are separated into Free on Board (FOB) costs of the intermediate bioenergy carrier, costs related to setting up and operating an upgrading facility, and costs related to sea transport.

7.1.1. Feedstock cultivation

Costs of biomass feedstocks are, analogous to fossil feedstocks, often displayed in a cost-supply curve. This visualizes the fact that first the most costs beneficial feedstocks will be used. When the demand rises, feedstocks that are increasingly difficult to collect, and consequently more expensive, will be used. For most biomass types, cost data were not available for every studied region. In this case, the largest cost contributors are determined and data from known regions are scaled to estimate values for regions in which data was unavailable.

Vegetable and waste oils are commodities from which prices are publicly available. For vegetable oils, the processing steps from harvesting, collecting, and pressing into oil are not considered in detail. FOB prices for vegetable oils and waste oils in different ports are converted to estimate prices in all considered regions.

According to De Wit and Faaij [45], the costs of agricultural and forestry residues are dominated by the transport costs from the harvesting site to the plant gate. To estimate cost-supply curves for all studied feedstock region combinations, a base feedstock price is used in combination with increasing inland transport costs, which are further discussed in section 7.1.3. The base feedstock costs are defined as the costs that are allocated to the feedstock until the gate of the harvesting site.

Agricultural and forestry residues are both considered waste streams and therefore their production costs are assumed to be zero [46]. However, there are costs associated with the collection and field transport of these feedstocks De Wit and Faaij [45]. For Europe, values from Hoogwijk and Graus [75], De Wit and Faaij [45], Allen et al. [18] and Ericsson et al. [61] are used. Because the costs for both agricultural and forestry residues are dominated by collection and field transport, the costs in Europe are scaled with a combination of regional labor costs and gasoline prices to obtain values for all other regions. The used labor and gasoline costs per region are depicted in figure 7.1.

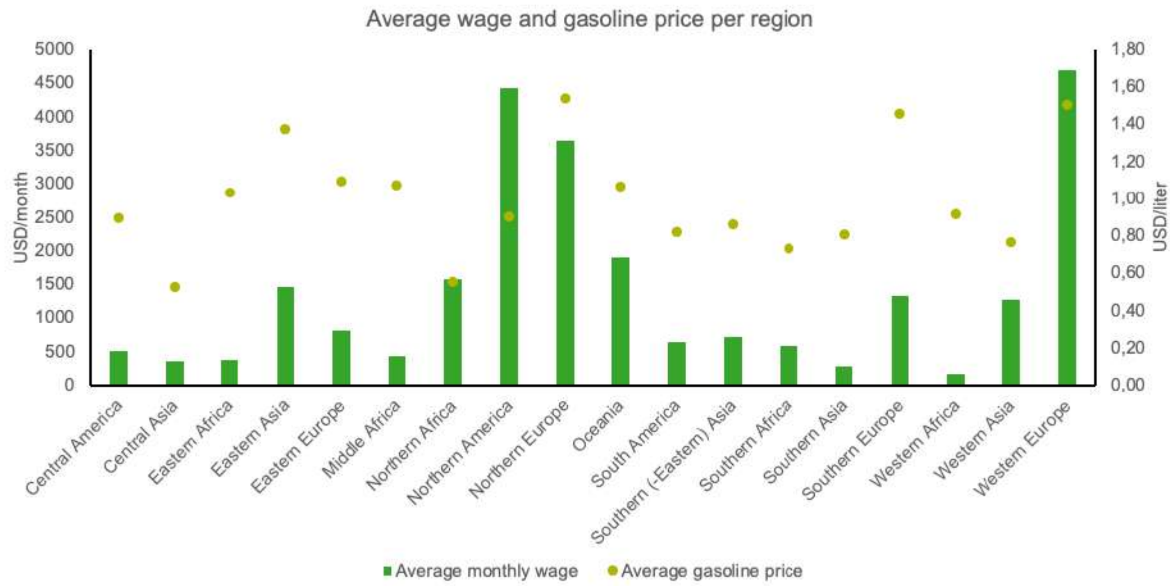

Figure 7.1: Average monthly wages and gasoline price per region [11, 12].

Energy crops are grown for energy production and are thus not considered as residues. This terminology in general includes lignocellulosic, oil, sugar, and starch crops. In this thesis, the term energy crops is used solely for lignocellulosic crops. Lignocellulosic crops can be further categorized into woody and herbaceous crops. For the purpose of this thesis, these two categories are lumped together under the title energy crops.

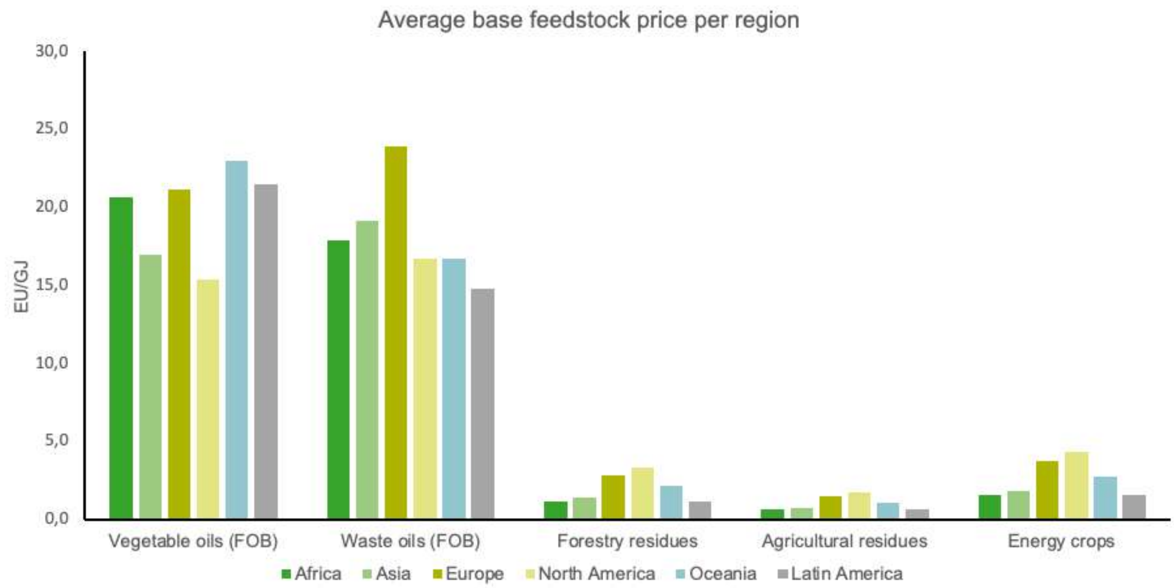

Figure 7.2: Unit costs of the considered feedstocks for every region studied in this thesis.

Costs of perennial grasses from Ericsson et al. [61] are used for Europe. De Wit and Faaij [45] made an in-depth calculation of the costs of energy crops. He discerned four costs factors, land costs, fertilizer costs, labor costs, and capital costs. The factors that dominate the costs of energy crops are land costs, wage level, and production efficiency [45]. Land costs are influenced by factors like fertility and the scarcity of land. Determining the variation in land costs per studied region is a study on its own and is left outside the scope of this thesis. Therefore, the base costs of energy crops are scaled with regional labor costs and gasoline prices. Hoogwijk and Graus [75] estimated the costs of residues and energy crops for all world regions. However, they found residue prices to be uncertain. As an example, they indicated residue prices in OECD Europe to be between 0.9 and 10.5 EU/GJ, which is an extremely large range. The influence of thus uncertainty in feedstock costs on eventual biofuel costs will be clarified in section 8.2.

Liquid waste and solid waste are considered as residue streams. In contrast to agricultural and forestry residues, these waste types can be collected in centralized waste collection plants. This causes gathering and transport costs to be zero. In some cases, even a credit for the uptake of these streams is provided. A summary of the unit feedstock costs used for the scenario analysis is depicted in figure 7.2. Alves et al. [20] states that "Biomass feedstock cost plays a major impact on the operational costs of a plant and the uncertainty associated with the feedstock supply is the most critical aspect of biorefineries profitability". Feedstock costs have a significant impact on refinery operating costs but are at the same time uncertain. Hence, feedstock costs should be further studied in the sensitivity analysis in section 8.2.

7.1.2. Processing and upgrading

As stated earlier, this study considers a distributed two-stage biofuel supply chain. This induces the physical separation of the processing and upgrading facilities. The processing facilities are built in the origin region where the biomass is supplied. Therefore, the costs related to processing and upgrading are separated as well.

Processing costs are defined as the expenses related to the conversion of biomass to the intermediate bio-energy carrier. On the other hand, upgrading costs are associated with the upgrading of the intermediate bio-energy carrier to a biofuel that can be used in an ICE. In this section, unit costs for both the processing and the upgrading steps are estimated. In most literature sources, costs for processing and upgrading were not separated. For FP, unless stated otherwise, a ratio for capital expenses of 40% and 60% for processing and upgrading respectively, was taken from Shemfe et al. [120]. For HTL, the same ratio was applied, taken from Tzanetis et al. [129]. In the case of gasification and Fischer-Tropsch synthesis, the ratio was 43% and 57% respectively, which is taken from Swanson et al. [125].

Processing costs

For the processing step, no distinction is made between fixed and variable costs. The total costs are divided by the refinery output to obtain an average fuel price per energy unit. In reality, these costs would also be dependent on plant size, but this is left outside the scope of this research, because general FOB costs for the intermediate bio-energy carrier are assumed. Also, scale effects are assumed to be minor for the processing plants because they are expected to be smaller, more distributed and in vicinity to the feedstock source. Region-specific location factors are used to estimate regional price differences in the production of intermediates.

For vegetable/waste oils at source prices are available, making further estimations of costs related to oil extraction unnecessary. Only the processing costs related to transesterification and hydro-treatment of the oils are taken into account. Values from various literature sources for the costs related to fast-pyrolysis, HTL and gasification FT are given in Appendix D.1.

According to Zhu et al. [143], capital costs for HTL are higher than for fast-pyrolysis. He states that, "compared to other major biomass conversion technologies, such as pyrolysis or indirectly-heated gasification, the HTL technology is more expensive for the capital cost. The major reason is the much higher operating pressure and the more expensive shell-and-tube design for the HTL reactors compared to a pyrolyzer or gasifier.".

Upgrading costs

The costs of upgrading the intermediate bio-energy carrier to the eventual biofuel are divided into fixed and variable costs. In the overall cost calculation, a part of the OPEX are assumed to be fixed OPEX and are periodically paid, regardless of the production rate. The other part of the OPEX is dependent on the output of the refinery. The capital investment is treated separately. Most considered studies estimated the capital expenses assuming "n^{th}-plant" construction. This entails the assumption that the plant construction and operation are based on a well-established design process and thus neglects the additional costs that are related to the set up of a "first-of-a-kind" plant [126]. The general evolution of the production costs associated with the implementation of a new technology are shown in figure 7.3. Although a first-of-a-kind plant can be expensive, the overall influence of these costs over a longer period of time are considered to be negligible.

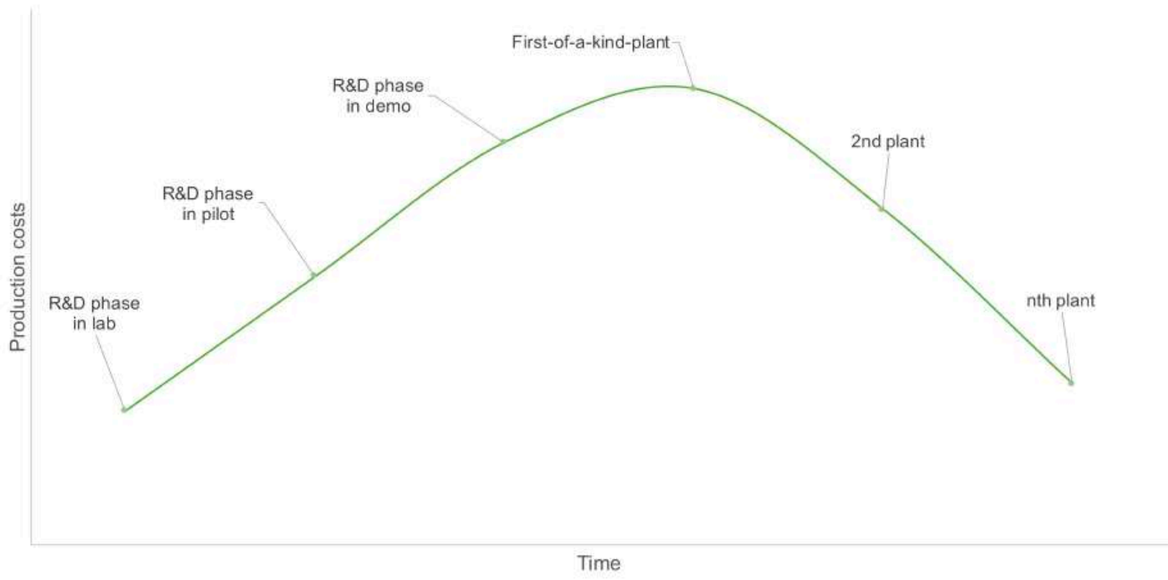

Figure 7.3: General evolution of production costs for a new technology. Partly adapted from Landälv et al. [89].

A significant part of the fixed costs is related to the Total Capital Investment (TCI) of setting up a processing facility. To calculate the TCI, usually first the Total Purchased Equipment Costs (TPEC) are estimated. The TPEC include all pieces of equipment that are required to run the conversion process. Multiplying the TPEC with a lang factor, the TCI of a plant can be estimated. For a process that includes fluids, this factor lies between the 4,92 and 5,1 [40]. Accordingly, the TCI can be annualized over the lifetime of the plant. In this study, a Capital Recovery Factor (CRF) of 0,12 is used, which corresponds to a refinery lifetime of 20 years and a 10% discount rate. To compare various studies that estimated the TCI of a processing facility, all values are scaled to a yearly 2,78 PJ input and 2,18 PJ input for processing and upgrading respectively. A scaling factor of 0,7 is used with formula 7.1 [126]. The feedstock input rate is based on the HTL facility of de Jong [40]. All monetary values taken from literature were standardized to $M€$ (2020). If a plant was designed in a certain region, a location specific correction factor, obtained from Intratech Solutions was applied.

$$Investment_{scaled} = Investment_{base} \cdot (\frac{Capacity_{scaled}}{Capacity_{based}})^n \tag{7.1}$$

Fixed OPEX includes local taxes, insurance, plant overhead and administrative costs. Variable costs include among others, operating labor, utilities and maintenance. Feedstock costs have a significant contribution to the overall fuel costs, but these were already discussed in section 7.1.1. In figure 7.4, the average costs items obtained from the literature are shown. A more detailed overview of this literature study is given in appendix D.1. FAME and HVO are already commercial at this stage. Capital Expenditures (CAPEX) and OPEX related to the production of these fuels are obtained from a report of Landälv et al. [89]. They compared three cost scenarios for the production of FAME and HVO and stated that OPEX for HVO production are in the range of 100-200 USD/ton, excluding feedstock costs. Feedstock costs are the most significant item in the production costs for both FAME and HVO. The high cost scenario of Landälv et al. [89] is taken for both FAME and HVO.

Upgrading of fast-pyrolysis oil is more expensive than upgrading of HTL oil. This is caused by the higher energy density of bio-crude that is produced during HTL. Hence, less hydrogen is required to upgrade the fuel to the desired specifications. Meyer et al. [103] performed a techno-economic assessment for fast pyrolysis and upgrading of lignocellulosic feedstocks. From his research can be stated that about 50% of capital investments are related to the upgrading facility and hydrogen plant.

From figure 7.4, it is evident that FT-synthesis is expensive. This is mainly caused by the relatively low conversion yield of syngas to FT-diesel, increasing the costs per unit of energy.

7.1.3. Inland and sea transport

As stated in the previous section, the costs of agricultural and forestry residues are dominated by the transport costs from the harvesting site to the plant gate. De Wit and Faaij [45] indicated that the average forest

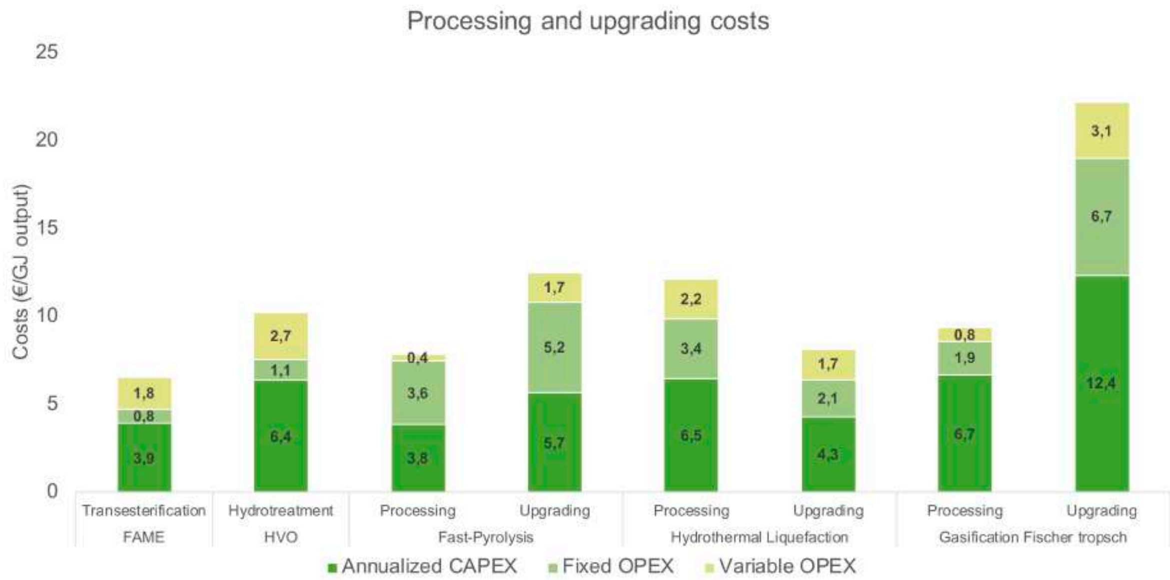

Figure 7.4: Average processing and upgrading costs, obtained from various literature sources given in Appendix D.1.

density and the size of the processing facility influence the costs of forestry residues. This is mainly because a higher forestry density increases the difficulty of collecting feedstocks, and increases the distance from the harvesting site to the plant gate.

Due to the large influence of inland transport costs on the total feedstock costs, this variable is used to create cost-supply curves for every feedstock and region combination. Usage of this relationship between cost and supply was previously explained in section 4.2.1.

To determine the amount of distance that the biomass needs to be transported, an average base distance for every region is selected based on the size of the region. Lamers et al. [88] optimized biomass trade on a similar geographical scale. They assumed an average base distance of 400 km for Brazil. This value is increased to 600 km for the entire South America region. Consequently, the base distance for all other regions is scaled relative to South America, based on the ground area of each region.

When a certain amount of biomass is collected from this region, the average distance goes up. This way, the increasing difficulty of feedstock collection and the rising inland distance are mimicked. It is difficult to find cost-supply curves for every feedstock region combination. For Europe, cost-supply curves from De Wit and Faaij [45] are approximated. For the other regions, the maximum supply potential is used to divide the total supply into different parts, assigning a unit cost to every part. Additionally, in every region average costs of truck transport are determined in EU/ton-km. Figure 7.5 shows an example of a cost supply curve of Western-Europe. This only entails the unit inland transport costs.

7.2. Environmental parameters

The sustainability of biofuel use is dependent on the emissions that can be attributed to its lifetime. To holistically evaluate the environmental performance of biofuels, the entire supply chain, from well-to-wake, needs to be taken into account [126].

It is not intended to pursue a detailed LCA, but rather to obtain unit emissions that can be used in the supply chain optimization. State-of-the-art literature is used to obtain unit GHG emissions for each stage in the marine biofuel supply chain. The marine biofuel supply chain, as studied in this research, can be split up into separate stages shown in figure 7.6.

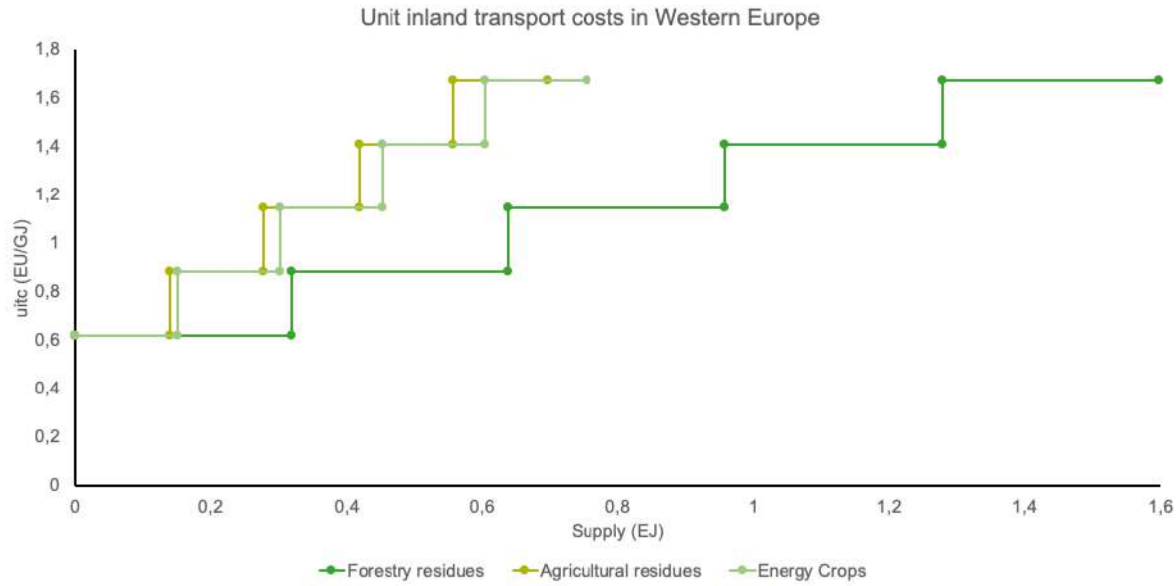

Figure 7.5: An example of a cost supply curve for Western Europe.

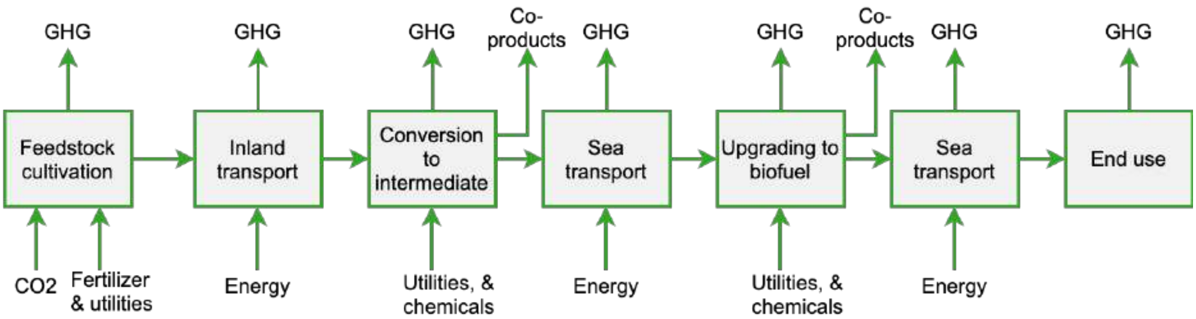

Figure 7.6: Different stages of the marine biofuel supply chain. Partly adapted from De Jong et al. [41].

According to [40], "LCA methodologies and default values are often standardized within a certain regulatory context". The RED II also contains a standardized LCA methodology. A simplified version of this methodology in combination with various literature is used in this thesis to estimate unit emissions per phase and technology. The simplified well-to-tank emission calculation method used in this thesis is given in formula 7.2.

$$E = e_f + e_p + e_{it} + e_u + e_{st} \tag{7.2}$$

The unit emissions used in the optimization model correspond with the decision variables that optimize the flow between the nodes in the network, shown in chapter 4. Because the flow in the model is determined in PJ, the used functional unit is ktonCO2-eq/PJ, which equals to gCO2-eq/MJ. Emissions that are emitted by the construction of new plants is not taken into consideration.

7.2.1. Feedstock cultivation

Unit emissions related to the cultivation (e_f) of feedstocks are obtained from RED II. Values were given as gCO2-eq/MJfuel and were converted to gCO2-eq/MJfeedstock, using formula 7.3, which is obtained from the RED II.

$$e_f feedstock = \frac{e_f fuel}{Yield \cdot Allocation factor} \tag{7.3}$$

The yields used for this calculation are discussed in section 7.3.2. The allocation factor is the ratio of energy in the fuel and its co products. Product ratios for the different technologies were used from de Jong [40] to estimate the allocation factors. In the case of FAME production, glycerin is formed as a by product. For the remainder of the technologies it is assumed that there are no co products. This results in the unit emission factors for feedstock cultivation shown in table 7.1. Emission factors of solid and liquid waste are set to zero, but these could even be negative when the prevention of landfill or incineration is taken into account.

Table 7.1: Emission factors used for the cultivation of feedstocks. For vegetable oils, the oil extraction is included.

Category	Data source	Value from source (gCO2-eq/MJfuel)	Allocation factor	Average (gCO2-eq/MJfeedstock)
Vegetable oil	RED 2	26,1	96%	27,5
Waste oils	RED 2	0	96%	0
Forestry residues	RED 2	5,3	100%	5,3
Agricultural residues	RED 2	1,12	100%	1,12
Energy crops	RED2	4,4	100%	4,4
Liquid waste	RED 2	0	100%	0
Solid waste	RED 2	0	100%	0

7.2.2. Processing and upgrading

For the unit emissions related to the conversion of biomass to the intermediate (e_p, and upgrading (e_u) values from various studies are used. Determining unit emissions for the entire well-to-tank phase of the studied pathways is not straightforward. During the conversion process, not only transportation fuel but also various (non-) energy co-products, like electricity and different fuel fractions, are produced.

Additionally, there are different methods to allocate unit emissions over the main product and co-products. Emissions can be allocated to products by economic, energy, mass, or displacement allocation. The displacement method entails co-production credits if the excess electricity of the process is sold on the market as green electricity. In the LCA of De Jong et al. [41], unit emissions for bio-jet fuel were determined to assess its environmental performance. They made a comparison between the four different allocation methods and discovered a difference between allocation methods of about 10 gCO2-eq/MJ. In this study, only the energy allocation method is used, seeing that this it the most widely used method.

To reduce the GHG emissions produced during the processing phases, of-gasses of the processes can be captured to produce hydrogen. This way of producing hydrogen is significantly more beneficial for the reduction of GHG emissions than buying natural gas from external sources [41]. This is especially true for fast-pyrolysis because the resulting bio-oil requires generous amounts of hydrogen for the upgrading while the of-gasses already contain significant quantities of it. From the study of De Jong et al. [41], it became evident that hydrogen is the main factor in emissions caused by processing and upgrading. Seeing that hydrogen is mostly used during upgrading, a considerable part is assigned to this part of the process. The emission factors used that are used as input, are shown in table 7.2.

As stated in the scope of this thesis, no distinction is made in the different fuel fractions. Also, the yields discussed in 7.3.2, are taken as a ratio of the energy in the fuel and do not include electricity production. FT-diesel has a considerably higher emission saving potential compared to the other technologies, which is “mainly caused by the self-sufficiency of the process and excess electricity production” [41]. The main source of information for the unit emission data is the LCA of De Jong et al. [41]. It is to be noted that these figures do not include emissions caused by ILUC. Therefore, eventual results might be slightly over or underestimated.

Table 7.2: Emission factors used for processing and upgrading of the different conversion pathways.

Process	Source	Unit emissions (gCO2-eq/MJ)	Process	Source	Unit emissions (gCO2-eq/MJ)
Oil extraction	RED 2	3,4	(Trans-) esterification	RED 2	12,2
Pre-treatment + Fast-pyrolysis	De Jong et al. [41]	1	Hydrotreatment (HVO)	RED 2	10,5
Pre-treatment + HTL	De Jong et al. [41]	1	Fast pyrolysis upgrading	De Jong et al. [41]	20
Pre-treatment + Gasification	RED 2	2	HTL upgrading	De Jong et al. [41]	15
			Fischer Tropsch	RED 2	0

Seeing that hydrogen is the most significant contributor, it might be necessary to study this in further detail. For example, hydrogen might become green in the nearby future, causing it to be carbon neutral. In this thesis, the scope is narrowed to two-stage facilities, which induces the need for externally sourced hydrogen, seeing that the processing and upgrading phases are physically separated. As mentioned earlier, the influence of using external fossil hydrogen is especially important with fast pyrolysis. De Jong et al. [41] indicated that the difference in GHG emissions can reach around 18 gCO2-eq/MJ between fast pyrolysis in and ex-situ.

Another uncertainty in the emission factor related to biofuel upgrading is the extent to which upgrading is required for marine biofuels. The upgrading emission values from De Jong et al. [41] are associated with Renewable Jet Fuel (RJF), which is a light fraction of the distillation process. Fuels for the aviation industry might require more upgrading than marine biofuels, which could decrease the emissions related to the upgrading process. The mentioned uncertainties regarding hydrogen use for fuel upgrading are further discussed in the sensitivity analysis in section 8.2.

7.2.3. Inland and sea transport

Unit emissions from inland transport (e_{it}) are calculated by multiplying the transport distance with fixed values of 62 and 22 gCO2-eq/ton-km for road and rail transport respectively. These values were taken from McKinnon and Piecyk [101]. Similar to inland transport costs, inland transport emissions are a function of the distance. Therefore, when the supply increases, unit emissions per unit of feedstock also increase. The same method as explained in section 7.1.3 is used to mimic this effect.

Unit emissions from sea transport are highly dependent on the vessel type, trade route, and corresponding vessel utilization rate. Intermediate bio-energy carriers could be shipped using either product or chemical tankers. To estimate the emissions related to the mobilization of the intermediate and end products, a distinction is made between short-sea and deep-sea shipping. For short-sea and deep-sea shipping, average emission factors of 16 and 12 gCO2-eq/ton-km are used respectively [101].

As previously mentioned, it became apparent from a report of McKinnon and Piecyk [101] that emissions per unit of cargo are highly dependent on the size of the vessel used. A 60.000 + dwt product tanker has an emission factor of around 5.7 gCO2-eq/ton-km. However, emission factors for product tankers of 5000 dwt are around 45 gCO2-eq/ton-km. Hence, there is a significant difference between shipment sizes and unit emissions. Additionally, the used emission factors are based on the use of fossil fuels. However, in the future, more and more sustainable fuels will be used. Both of these uncertainties are addressed in section 8.2.

7.3. Technological parameters

Several technological parameters are required as an input of the optimization model. These parameters are mostly used to model refinery plants. Refinery plants are modeled on a high level, using a black-box method, in which the output is determined by a fixed yield, dependent on the process. In the following paragraphs, the used plant sizes, scaling factors, conversion yields, energy contents, and technology introduction years are discussed.

7.3.1. Plant sizes and scaling

The optimization model, developed in this thesis, takes five different refinery sizes into account. FAME and HVO are both commercial fuels, and production volumes of commercial facilities are at this stage between 50.000 and 250.000 tons of product per year [89]. However, for the other three studied pathways, no commercial plants are yet in existence. Therefore, the sizes of commercial plants are not known. The size of a processing facility can be of significant influence on the cost of the product. When the possibility arises of constructing larger plants, economies of scale start to play a role. The fixed costs can be shared over a larger product output, leading to a more cost-efficient end product. However, this effect is not boundless, from a certain point the benefits start to stagnate. Also, under-utilization is a significant risk of setting-up large facilities.

Besides economies of scale, capital costs are neither linearly dependent on the facility size. Usually, a scaling factor of 0.7 is used to scale between refinery sizes, using formula 7.1. But this effect is also not boundless. In the literature, often a plant size of 2000 tons of dry biomass input is taken. The yearly marine energy demand of the port of Rotterdam is about 0.75 EJ. A plant of 2000 tons dry biomass input would produce approximately 5.8 PJ of upgraded pyrolysis oil annually. Meaning that such a plant would be able to supply about 0.7 % of the total energy supply in the port of Rotterdam. It is therefore expected that future bio-refineries should become larger than this. However, there is no further literature found that dwell upon expectations of future bio-refinery sizes. Therefore, a 2000 ton dry biomass input is taken as the base size.

When looking at the fossil industry, refinery sizes are enormous. However, many of these refineries exist out of multiple plants situated next to each other. In both cases, economies of scale and increased efficiencies can lead to cost reductions. The often mentioned 2000 dry ton of biomass input per day is used as the base size. From there, a plant discretization of 5 steps is used, shown in table 7.3. Choice of refinery sizes can have an impact how economies of scale effects are calculated within the method. Therefore, the used scaling factor is also studied in the sensitivity analysis.

Table 7.3: Plant size discretization used in this study.

	Small	**Medium**	**Large**	**Very Large**	**Ultra Large**
Max input ($PJ_{intermediate}/year$)	6	12	18	24	30

7.3.2. Process yields and energy content

Process yields are defined as the amount of biofuel that can be produced from a certain quantity of biomass. In this case, two conversion yields are of importance, the yield from biomass to the bio-intermediate and the yield from the bio-intermediate to the biofuel end product. In the literature, yields are either expressed by weight or energy ratio. The energy content of the products is closely related to the conversion yield and can be used to translate weight percentage yields to yields on an energy basis.

Conversion yields are dependent on the process conditions and the molecular composition of feedstocks. For example, grain residues have high ash content which can reduce their conversion yield [126]. Examples of process conditions that can affect the yields are temperature, solvent-to-feedstock ratio (for fast pyrolysis), and the fluidizing medium (for gasification Fischer-Tropsch) [126].

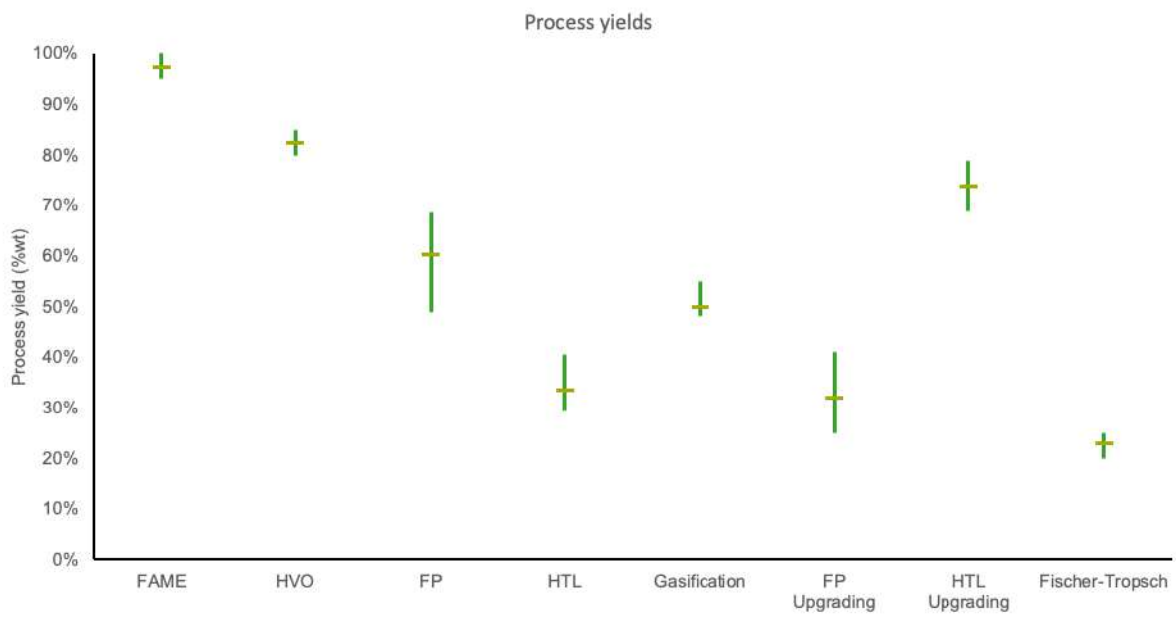

Figure 7.7: Yields on a weight basis for the different conversions in the scope of this thesis. Data from: [24, 31, 32, 36, 72, 84, 89, 89, 96, 102, 103, 107, 109, 115, 117, 120, 121, 125, 126, 129, 141, 143]

In reality, every specific feedstock and thermo-chemical conversion process combination might have a different yield and a different energy content of the end product. There exist a trade-off in the technical efforts required to transform a feedstock into fuel and the economic/environmental performance of that feedstock. This trade-off is visualized in figure 7.8.

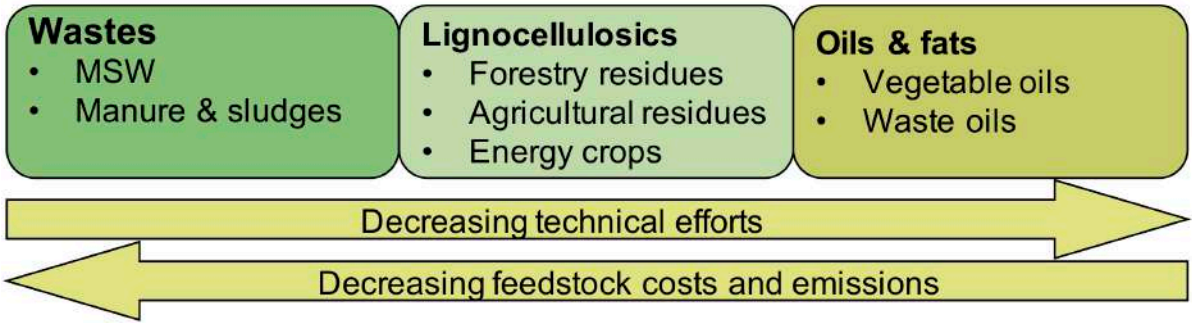

Figure 7.8: Trade-off between technological difficulty and economic/environmental feedstock performance. Partly adapted from El Takriti et al. [58].

To obtain a realistic estimation of these process yields, an average is taken from the values of different literature sources. To account for this uncertainty, the eventual consequences of variation in these parameters are taken into account in the sensitivity analysis performed in section 8.2. For the energy content, a fixed energy content per product type is taken from literature sources, always expressed in Lower Heating Value (LHV). Energy contents might vary slightly, but this variation is assumed to be negligible. For FAME and HVO technological parameters are already relatively known. For the other conversion pathways, various literature is consulted. Figure 7.7 depicts the results of this literature study, which is further elaborated upon in the following paragraphs.

In the transesterification process, in which FAME is produced, about 10% glycerol is added to the vegetable or waste oil, which causes the total fuel yield to be above 100% on a mass basis. The yield solely from UCO to FAME is around 97-98% on a mass basis [89]. The energy content of vegetable oils and FAME are similar, causing the process yield to be similar on a mass and energy basis.

Conventional yields for the hydro-treatment of oils to HVO are usually in the range of 80-85 % on a mass basis. On an energy basis, HVO yields can get close to 100%. An increase in the energy content is caused by the addition of hydrogen, which is also the main cost factor in the production process of HVO [89].

The yield of fast pyrolysis (dry biomass to pyrolysis oil) is found to be in the range 40-69 %wt [77]. For various agricultural residues, the bio-oil yields were found to be in the range of 56-69 %wt. For forestry residues, bio-oil yields are generally higher compared to agricultural residues [33]. Oasmaa et al. [109] indicated that for white wood, yields are found between 70-75 %wt. However, when bark and needles were included in the feedstock, the yield dropped to 60-65 % wt. Mullen and Boateng [107] found the bio-oil yield of switchgrass to be 60% wt. For MSW, bio-oil yields were even lower, ranging from 30-50 % wt including the aqueous phase, dependent on the reaction temperature [32]. This yield did not include the pretreatment of MSW into more energy-dense pellets. Therefore, the yield from untreated MSW to pyrolysis oil is found to be somewhat below 30%. It should be noted that the consistency of MSW is extremely unsure, which entails the very volatile energy content of this feedstock (ranging from 15 MJ/kg for food waste and 30 MJ/kg for plastic [121]). This leads to bio-oil yields that are not constant. To obtain a constant feedstock from MSW, significant pretreatment is required. From all the above-mentioned uncertainties, it appears that determining the bio-oil yields of MSW is difficult. To obtain a best estimate, the average of the found literature values is taken.

For HTL the process yield is generally somewhat lower than that of fast-pyrolysis. However, the bio-crude that is produced during HTL has significantly higher energy content than that of fast pyrolysis oil. This entails that less upgrading is required to obtain a fuel suitable for transport purposes. In the research of Tanzer [126], upgrading of the bio-crude was even considered unnecessary for marine fuel. She estimated the energy content of the bio-crude to be around 36 MJ/kg. HTL biocrude yields were found to be in the range of 29-41 %wt. Vardon et al. [136] indicated that for swine manure and anaerobic sludge, biocrude yields were 30 %wt and 9 %wt respectively. However, Tews et al. [127] indicated a biocrude yield of around 40 %wt for HTL of sewage sludge. In this thesis, biocrude yields for agricultural and forestry residues are assumed to be 31 % wt. For liquid waste, the value of swine manure is taken from Vardon et al. [136].

Table 7.4: Energy content of different substances used in this study.

Fuel	**LHV (MJ/kg)**	**Intermediate**	**LHV (MJ/kg)**	**Biomass**	**LHV (MJ/kg)**
FAME	37	Vegetable oil	37	Vegetable oil	37
HVO	44	Biocrude	36	Waste oils	36
FP	44	Bio-oil	17	Forestry residues	20
HTL	44	Syngas	18 (MJ/m3)	Agricultural residues	18
GFT	44			Liquid waste	20
				Solid waste	19
				Energy crops	18

For gasification Fischer-Tropsch, conversion yields are somewhat more difficult to find. Atsonios et al. [24] indicated a biomass to bio-jet fuel yield of 0.172 kg/kg_{feed}. Sarkar et al. [117] indicated a fuel yield of 12,96 %wt, from which 5.17%wt gasoline and 7.79 %wt diesel. According to the research of Swanson et al. [125], the total process yield for gasification Fischer-Tropsch is around 15%wt with an energy content for the end product of 42.7 MJ/kg. The efficiency of the gasifier was estimated by Swanson et al. [125] at 87.9% on an energy basis. However, for this thesis, gasification of the biomass and Fischer-Tropsch synthesis of the formed syngas is separated. Rafati et al. [115] stated that the process yield from syngas to FT-liquids is around 40% on an energy basis. The yields from Rafati et al. [115] and Swanson et al. [125] are used to estimate the separate yields of the gasification phase and the Fischer-Tropsch synthesis. This resulted in a gasifier yield (biomass to syngas) of 50% wt and a Fischer-Tropsch yield (syngas to FT -liquids) of 25 %wt. This corresponds to an overall yield of 13 %wt which is following the previously mentioned literature.

7.3.3. Introduction years of new technologies

An imported factor in the deployment of biofuels to the maritime industry will be the introduction years of the technologies that are currently only available on a small scale. The introduction year of new technology is defined as the year from which the technology becomes commercially available. Grijpma et al. [70] assumed that Fischer-Tropsch, stand-alone fast-pyrolysis, and HTL will become commercially available in 2020, 2023, and 2025 respectively. With current insights, these introduction years seem optimistic. The optimization model in this thesis simulates in time steps of five years. Because FAME and HVO are already commercially available, these biofuels are made available from the first period. Stand-alone fast pyrolysis and gasification Fischer-Tropsch are assumed to be commercial after 2025. Hydrothermal Liquefaction is expected to be commercial after 2030.

Assumptions concerning the introduction years of new technologies can have a significant influence on the end results. These new conversion technologies pave the way for the use of more abundant and cheaper feedstocks. Additionally, alternation in introduction years of technologies might lead to changes in the most feasible choices of new bio-refinery locations and trade-flows.

8
Model testing

In this chapter, the developed linear optimization model is tested. Firstly, in section 8.1 it is explained how the model is verified. Consequently, a sensitivity analysis is performed with the used model parameters. Section 8.4 covers the development of a Base Case (BC) scenario. The following subsections address the results that are obtained from running this BC scenario. To illustrate the trade-off between economical and environmental performance, section 8.3 shows the difference in outcomes when using both objectives. Lastly, the model is validated by comparing the outcomes with the literature.

8.1. Model verification

To verify that the developed model is correct and does not contain any bugs or inconsistencies, the following checks are performed.

- Unit check
- Flow equilibrium check
- Sensitivity analysis

Firstly, a unit check is performed to ensure that all parameters and input are given to the model with the correct units. Seeing that the network flows are determined in PJ, the cost and emission factors are feed-in EU/PJ and kton CO2-eq/PJ respectively.

Secondly, the network flows are tracked to ensure flow equilibrium in each network node. The ratio between inflow and outflow is determined by the conversion yields of the various conversion pathways. The results from the base case were checked on compliance with the imposed sets of constraints.

Lastly, a sensitivity analysis will be performed in section 8.2 to check whether the influence of certain parameters on the result was justified.

8.2. Sensitivity analysis

To address the uncertainty embedded in the parameter assumptions, a sensitivity analysis is performed on the base case. Performing such analysis results in a better understanding of the model and the influence of certain parameters on the output. For both objectives, the effect of varying parameter values was assessed. The results are shown in figures 8.1 and 8.2. It should be noticed that for every change in parameter values, the model will find a new optimal solution in which economic and environmental performance are considered. Hence, to show the influence of individual parameter changes in a more comprehensive fashion, sensitivity analysis for both objectives separately is attached in Appendix E.1. The results from the separate sensitivity analysis show approximately the same trend.

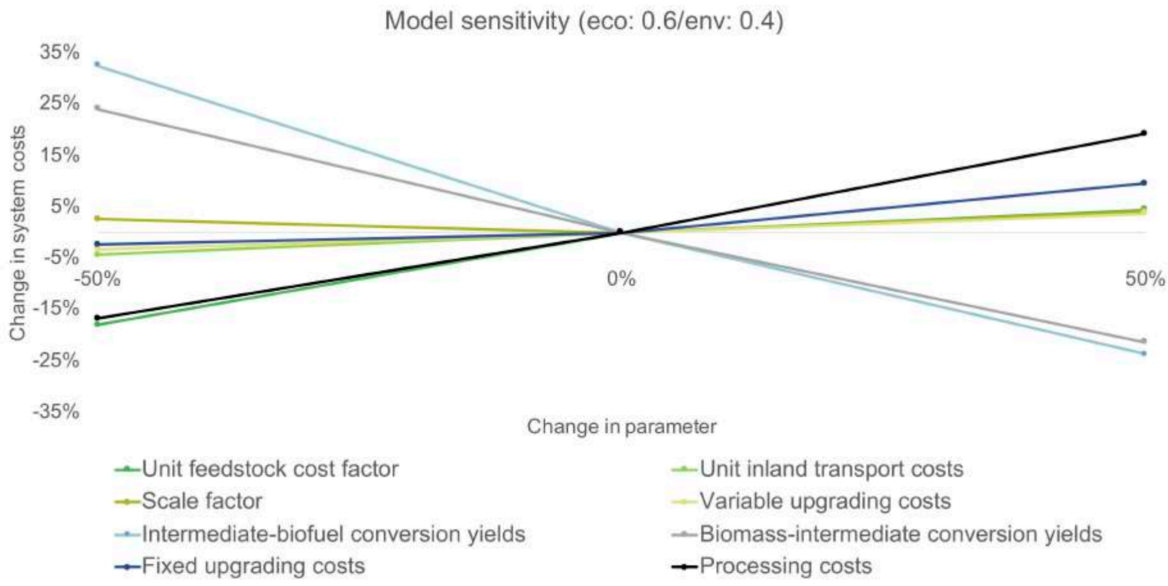

Figure 8.1: Economic sensitivity analysis, using combined weight factors.

It can be observed from figure 8.1 that influence of the unit processing costs on the eventual total system costs is significant. Judging from the studied literature, the expected uncertainty embedded in the processing costs is expected to be in the range of -50% to +50%. This entails a possible variation in total system costs of around 15%.

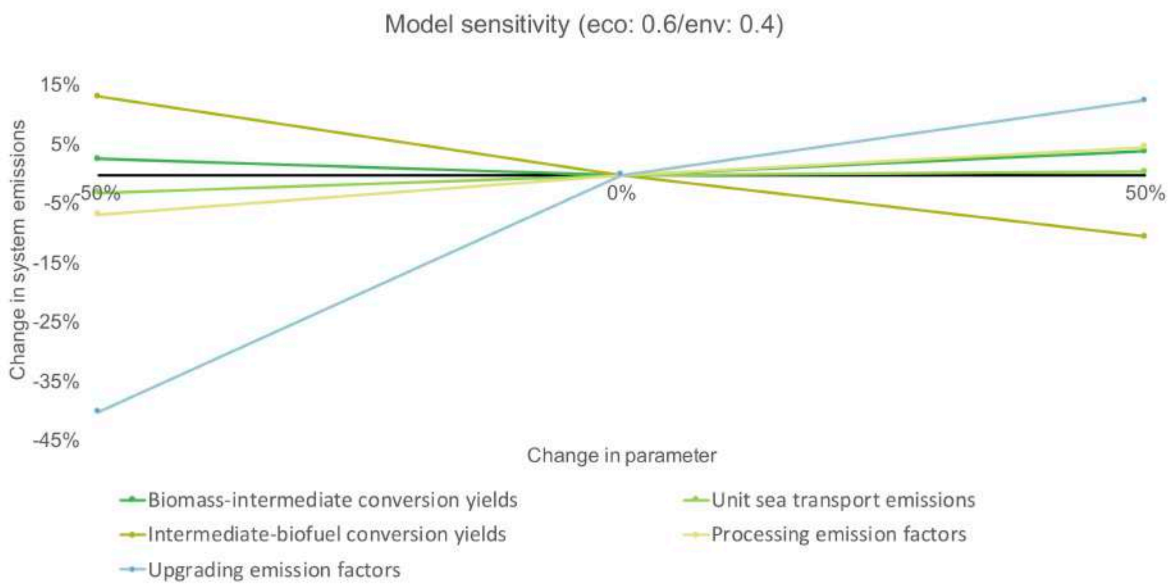

Figure 8.2: Environmental sensitivity analysis using combined weight factors.

From this analysis, the conversion yields appear to have a significant impact on both the change in total system costs and emissions. Consequently, increasing conversion efficiency over time could lead to large cost and emission reduction benefits. The maximum uncertainty in the different conversion yields is expected to be in the range of 10-20%. This leads to a change in total system costs of around 15% for the processing yield and upgrading yield. The upgrading yield has a lot more impact on total system emissions, which is again a result of the assumed use of gray hydrogen during this process.

Hence, the total system emissions are dominated by the use of hydrogen during the upgrading process. Transport also contributes to the overall system emissions, but this is minor compared to the emission contribution of externally sourced hydrogen. However, in figure 8.2 it is shown that reducing the emission factor of fuel upgrading has a larger effect than increasing it. This is caused by the model finding new trade-offs when the unit upgrading emissions are increased, leading to the choice of fuels that require less upgrading but have poorer economic performance.

Lastly, it was mentioned in section 7.2.3 that emission factors for transport can vary significantly between different trade-lanes and associated vessel types and sizes. The default emission factor was set to 12 gCO2-eq/ton-km. The maximum found emission factor for sea transport was 45 gCO2-eq/ton-km. This entails an uncertainty of around +300%. From the sensitivity analysis, it can be observed that a 50% increase of this parameter leads to a 0.5% increase in total system emissions. Hence, the maximum deviation in total system emissions would be in the range of 3%. It was also mentioned that fossil emissions factors are used. In the future, the increasing use of renewable fuel could drive this emission factor to be much lower. From the sensitivity analysis, it can be observed that a decrease of 50% in sea transport emission factor leads to a 3% decrease in total system emissions. Hence, setting the emission factor to zero would lead to a decrease in total system emissions of approximately 6%.

8.3. Illustrating the costs versus emissions trade-off

In section 8.4.1, the trade-off between economic and environmental performance was already visualized. To give a more explicit image of the differences in the solutions when giving more weight to the environmental side or economic side, the difference in resulting network flows is illustrated in this section. To achieve this, the model is used to develop the optimal solution for two different weight sets. The influence of assigning different weights on fuel choice is visualized in figure 8.3.

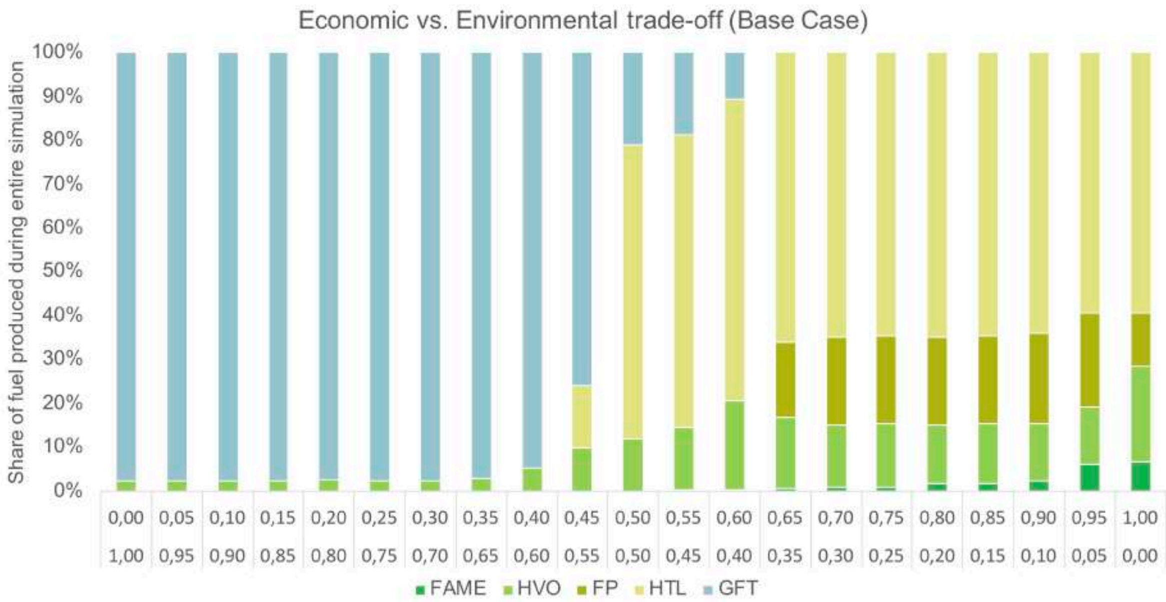

Figure 8.3: Fuel selection as a function of model weight factors for the base case scenario. The weight factor above represents the economic weight. Below represents the environmental weight.

The top row on the x-axis represents the economic weight, the lower row represents the environmental weight. It is evident from this figure that Gasification Fischer-Tropsch (GFT) has the strongest environmental performance. For the strongest economic performance, a combination of Hydrothermal Liquefaction (HTL), Fast-Pyrolysis (FP), HVO and FAME is chosen. To visualize the impact of the weight factors on bio-refinery locations, the economic and environmental objectives are isolated. The first set of weights neglects the economic objective, which results in the solution shown in figure 8.4.

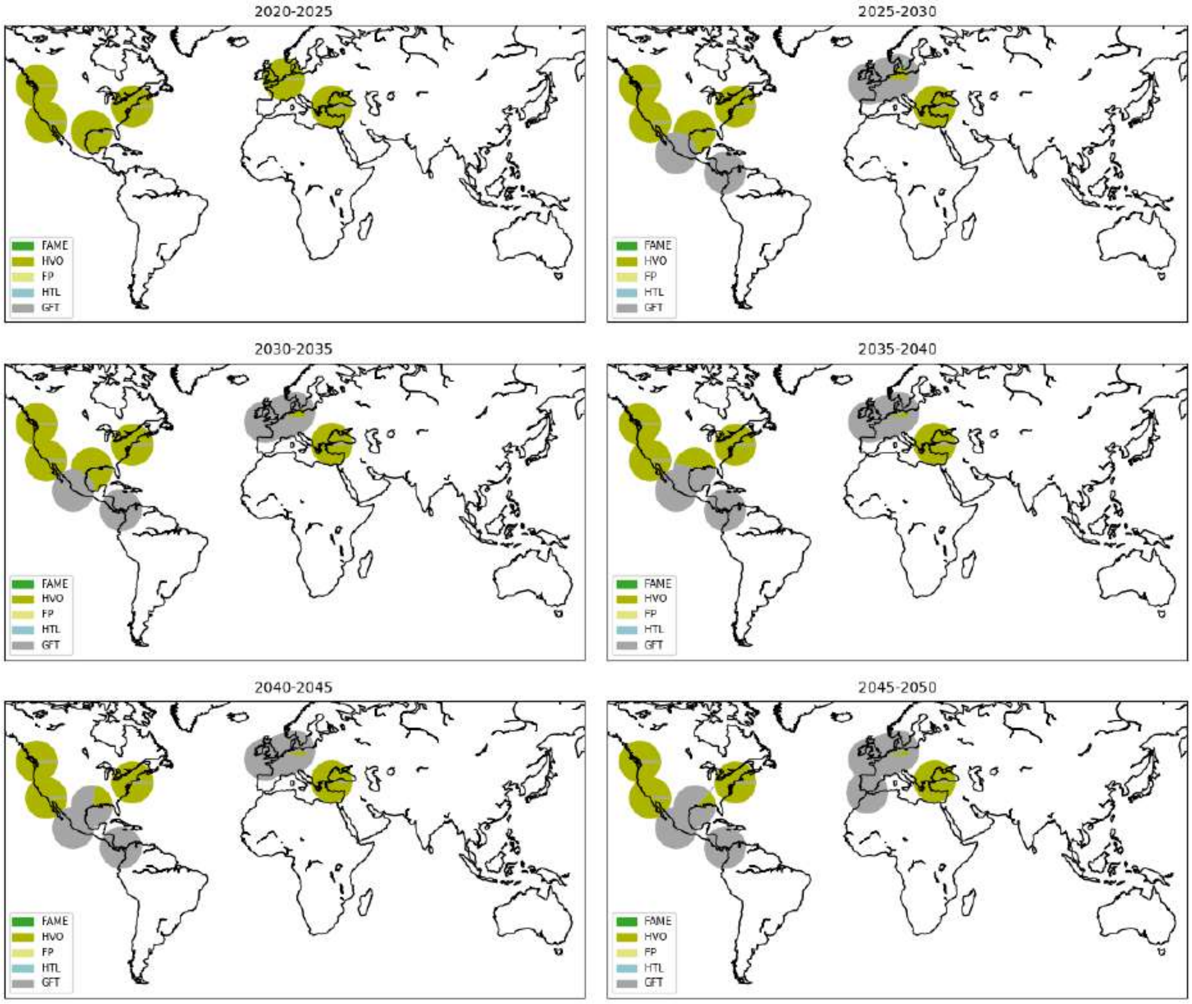

Figure 8.4: Optimal refinery types and locations for environmental objective

The result of assigning a large weight factor on environmental performance is visualized in the choice of refinery types and locations. The corresponding system flows are attached in Appendix E.2, which shows significantly more transport activity for the economic objective compared to the environmental objective. The model tends to use as much domestic biomass as possible. The biofuel deployment mix only consists of HVO and gasification FT, seeing that these fuels have the strongest environmental performance. Figure 8.3 shows the transition of fuel choice when varying the weight factors. This in contrast to the solution in which economic performance is preferred. The solution corresponding to the second set of weight factors is depicted in figure 8.5.

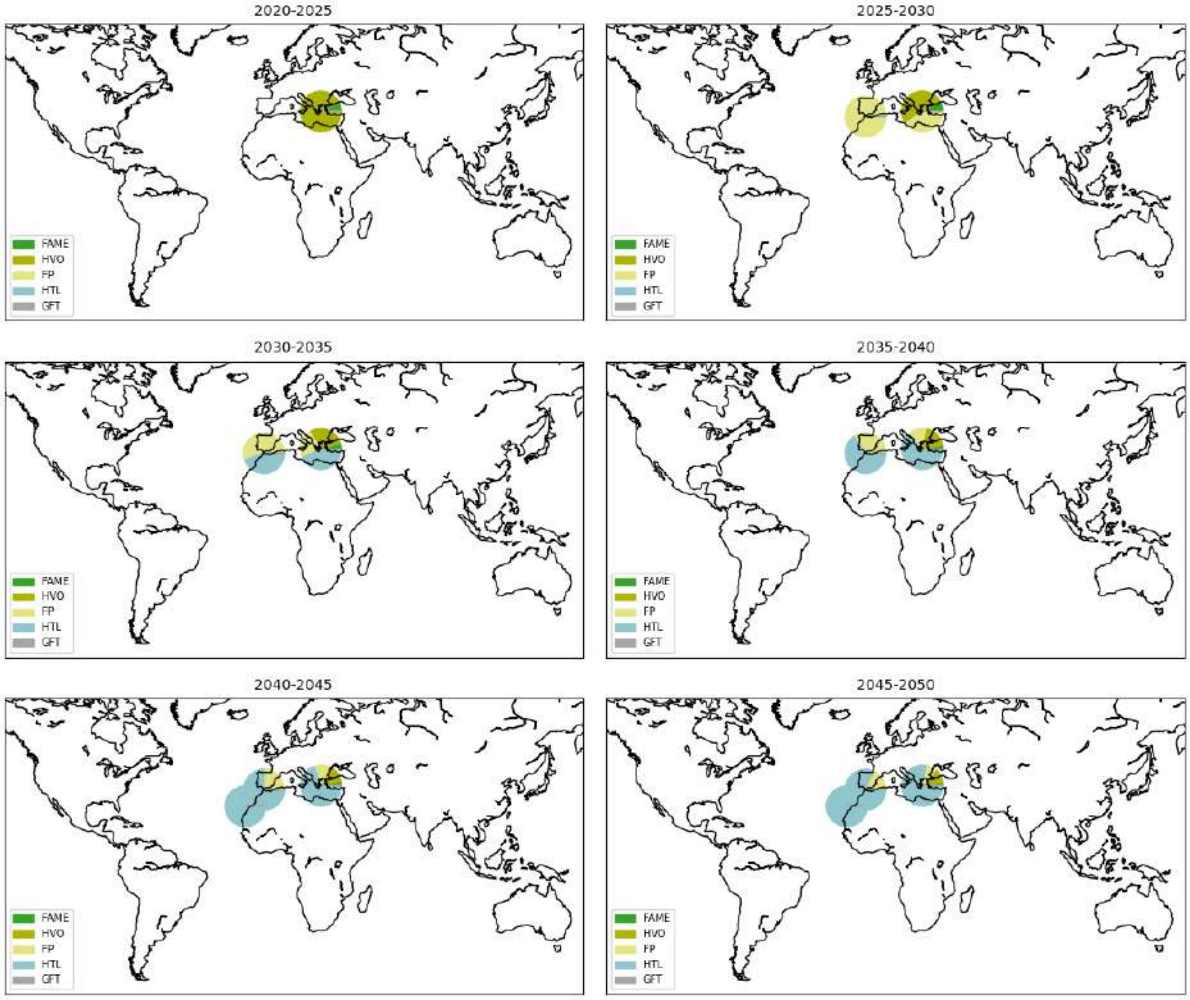

Figure 8.5: Optimal Refinery locations when isolating the economic objective.

It should be noticed that the second solution results in more centralized distribution of bio-refineries. Because environmental performance does not have the priority, sea transport is increased and more polluting, but cheaper fuel technologies are used. Eventually, the model converges to a situation in which HTL takes over almost all supply. This is due to its strong economic performance compared to fast pyrolysis and gasification FT.

Besides the strong performance of HTL, the possibility to use liquid waste feedstocks strongly decreases the feedstock costs related to this technology.

8.4. Base case scenario

To create a clear picture of the model behavior, a base case scenario is developed. The conditions of this base case scenario are shown in table 8.1.

Table 8.1: Conditions of the example scenario.

Supply scenario	**Energy demand scenario**	**Biofuel demand scenario**	**Technology introduction**
High	Medium	Most-likely	Fast pyrolysis and GFT from 2025-onwards HTL from 2030-onwards

The description of the supply and demand scenarios can be retrieved from chapters 5 and 6. The high supply scenario entails relatively low competition from other industries and a high level op biomass availability for the production of biofuels. The medium energy demand scenario assumes an energy growth scenario of the IMO that is not too pessimistic or optimistic. The most-likely biofuel demand scenario assumes that the most progressive countries include shipping in their GHG emission reduction regulations.

8.4.1. Marginal costs

An important element in assessing the potential of biofuels for the maritime industry, is the trade-off between the economic and environmental objective. Biofuels need to be competitive with fossil fuels and minimize emissions at the same time. To visualize the trade-off between costs and emissions, a marginal cost curve is provided. This curve shows the marginal costs of reducing GHG emissions compared to the situation in which conventional HFO would be used. To produce a marginal cost curve, the weights of the objectives are alternated from 0 till 1 in discrete steps of 0.05. The resulting graph is shown in figure 8.6.

Every point on the marginal costs graph represents a set of solutions, which is associated with the designated weight factors. The average costs are calculated by dividing the total system costs by the total amount of produced fuel over the entire period, obtaining an average fuel price in EU/GJ. To convert these values to EU/ton, the energy content factors discussed in section 7.3.2 were used. It should be noted that this marginal cost curve might change for different scenarios. Therefore, for every biofuel demand scenario, a new marginal cost curve will be developed.

For the remainder of this example, a weight factor for the environmental objective is chosen at 0.35 and the economic weight factor at 0.65. This results in an average fuel price of around 960 EU/ton for a reduction of 78.5 % compared to HFO, for the base case scenario. The relatively high environmental weight is required to prevent the model from proposing solutions in which intermediate bio-energy carriers or biofuels are shipped all across the world, for relatively low-cost savings.

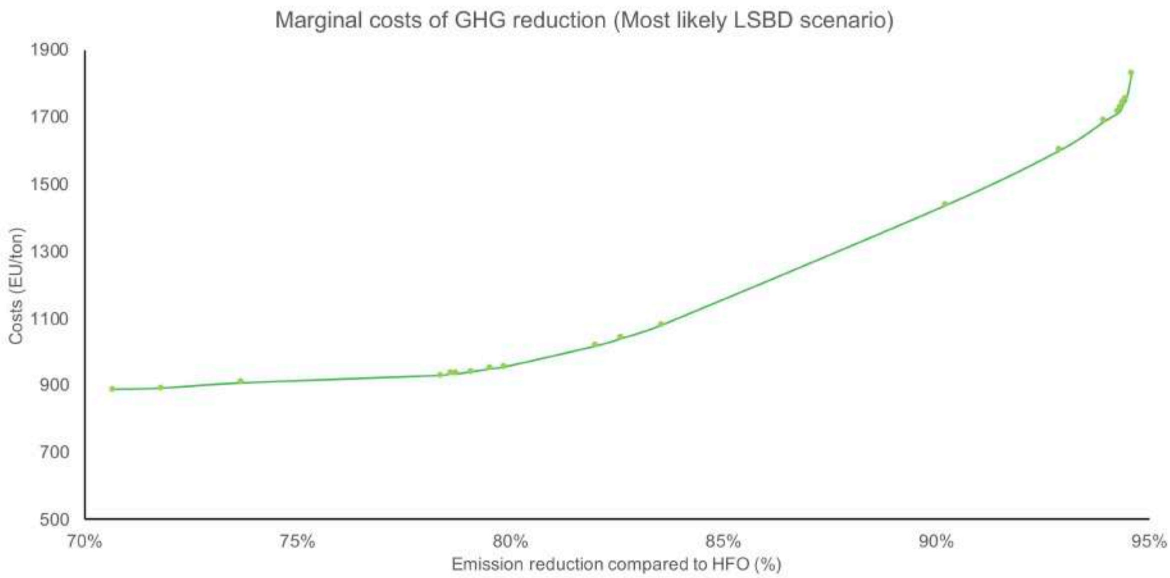

Figure 8.6: Marginal costs of reducing GHG emissions. WtW emission factor of HFO is set to 87.5 kg CO2-eq/GJ.

8.4.2. Refinery locations and system flows

Post-processing the model solution, first the decision variables are evaluated. Like mentioned earlier, these consist of system flow and refinery investment decisions. These decision variables are plotted on a world map to provide insight into the most feasible trade flows for this example case. Figure **??** shows the most feasible refinery capacity per fuel type and region. Figure 8.7 depicts the investment decisions in refineries over the studied period. Pie charts on the map indicate the percentage in the capacity required per conversion technology.

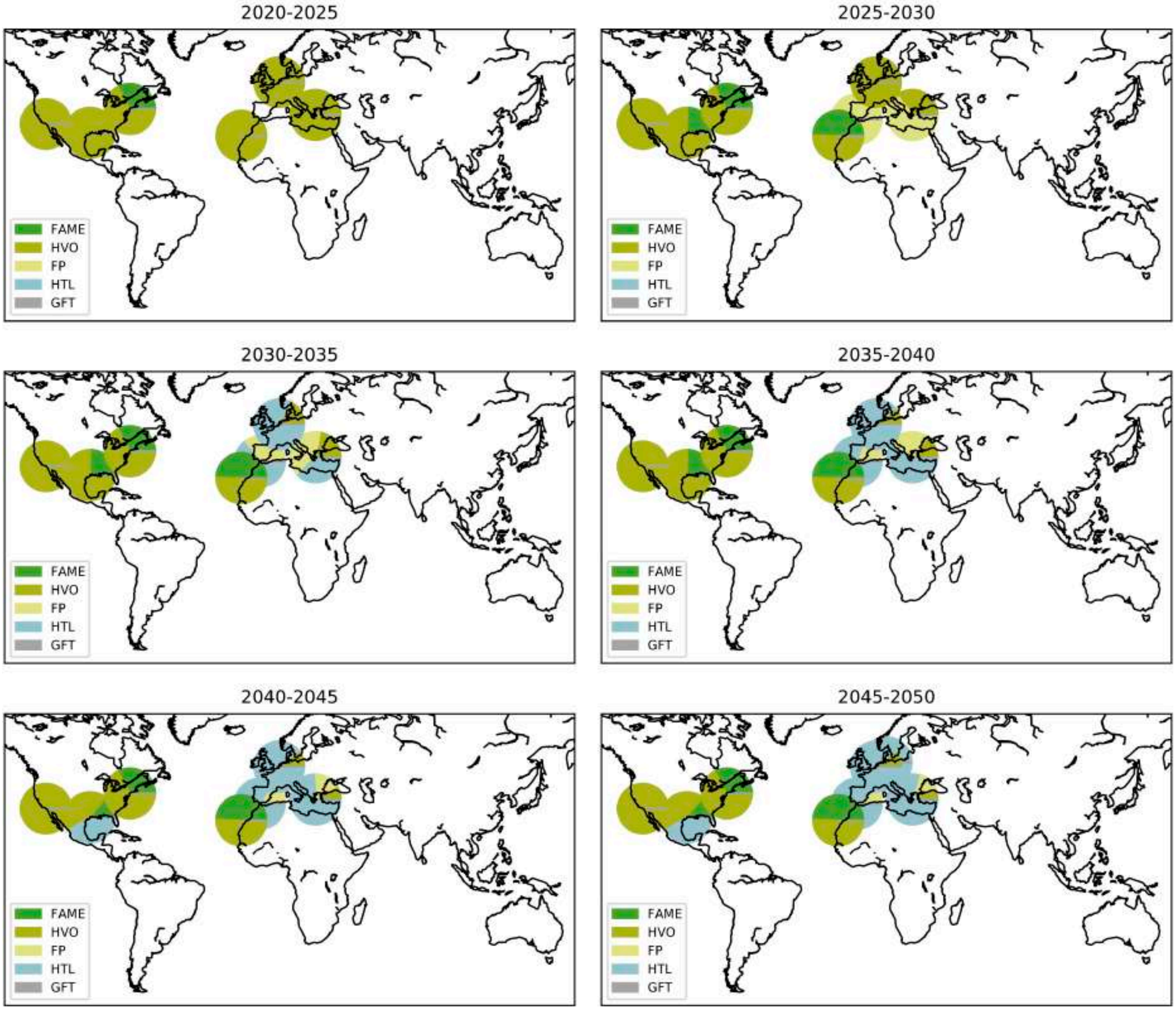

Figure 8.7: Refinery deployment in the Base Case scenario.

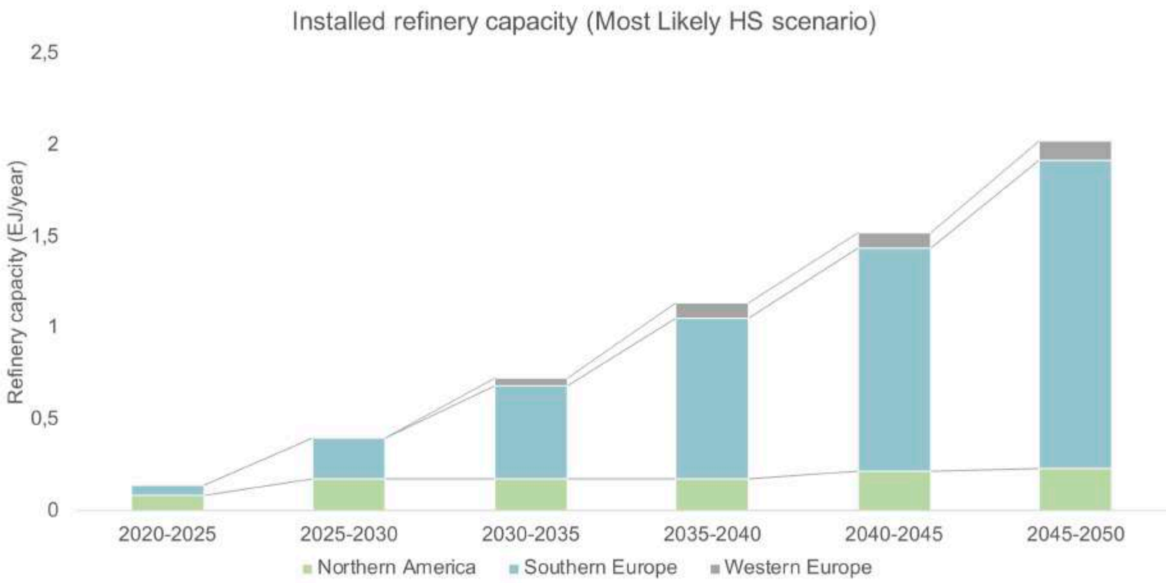

Figure 8.8: Required refinery capacity overtime in the Base Case scenario.

The model solution for this example case shows that at first HVO and FAME producing facilities are built. Eventually, the model incrementally increases the used amount of HTL and FP. It stands out that the setting-up of refineries for these advanced production technologies seems to be in Europe. This is most likely to be caused by the higher availability of waste oils in Northern America.

In figure 8.9, the most feasible trade-flows of the intermediate bio-energy carriers are shown. Mostly oils and fats are transported, while it seems that feedstocks for the production of advanced biofuels can be sourced locally.

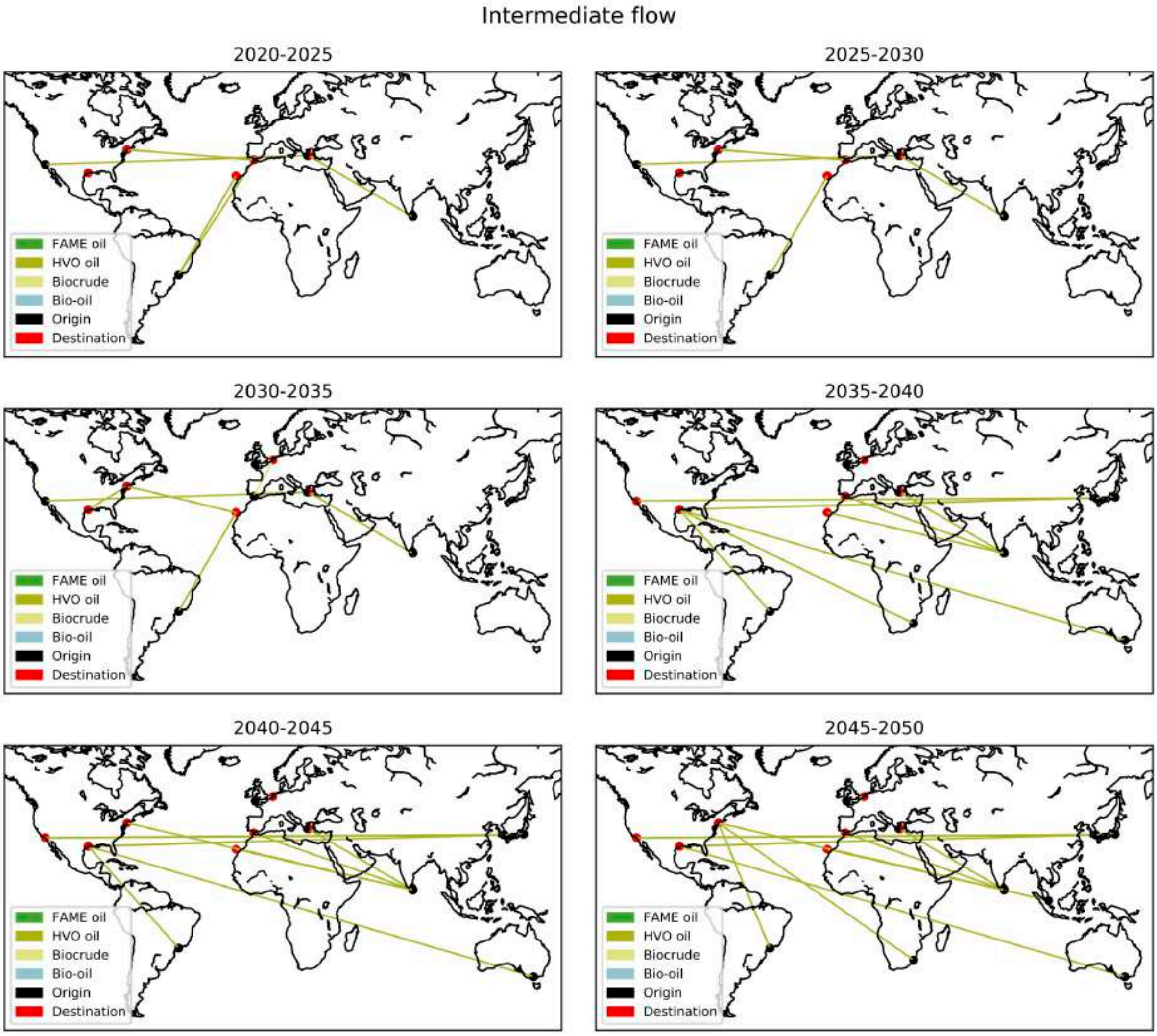

Figure 8.9: Flow of intermediate products in between nodes.

As indicated in figure 8.9, "FAME oil" and "HVO oil" originate mainly from Asia to the refinery locations. In the model "FAME oil" and "HVO oil" can be a mix of waste oils and vegetable oils. To gain more insight in the use of specific feedstocks per scenario, this topic is further discussed in section 8.4.4. The distinction between "FAME oil" and "HVO oil" is only implemented so that the model recognizes which part of the oily feedstocks is used for FAME and HVO production.

It should be noted that as soon as new technologies are introduced, the model decreases the use of FAME and HVO and increases the use of advanced biofuels. For this scenario, it seems that HTL provides the best trade-off between costs and GHG reduction. At the refinery locations, the intermediate is processed into the biofuel, which is transported to the demanding port. Figure 8.10 shows the trade-flows of these end-products.

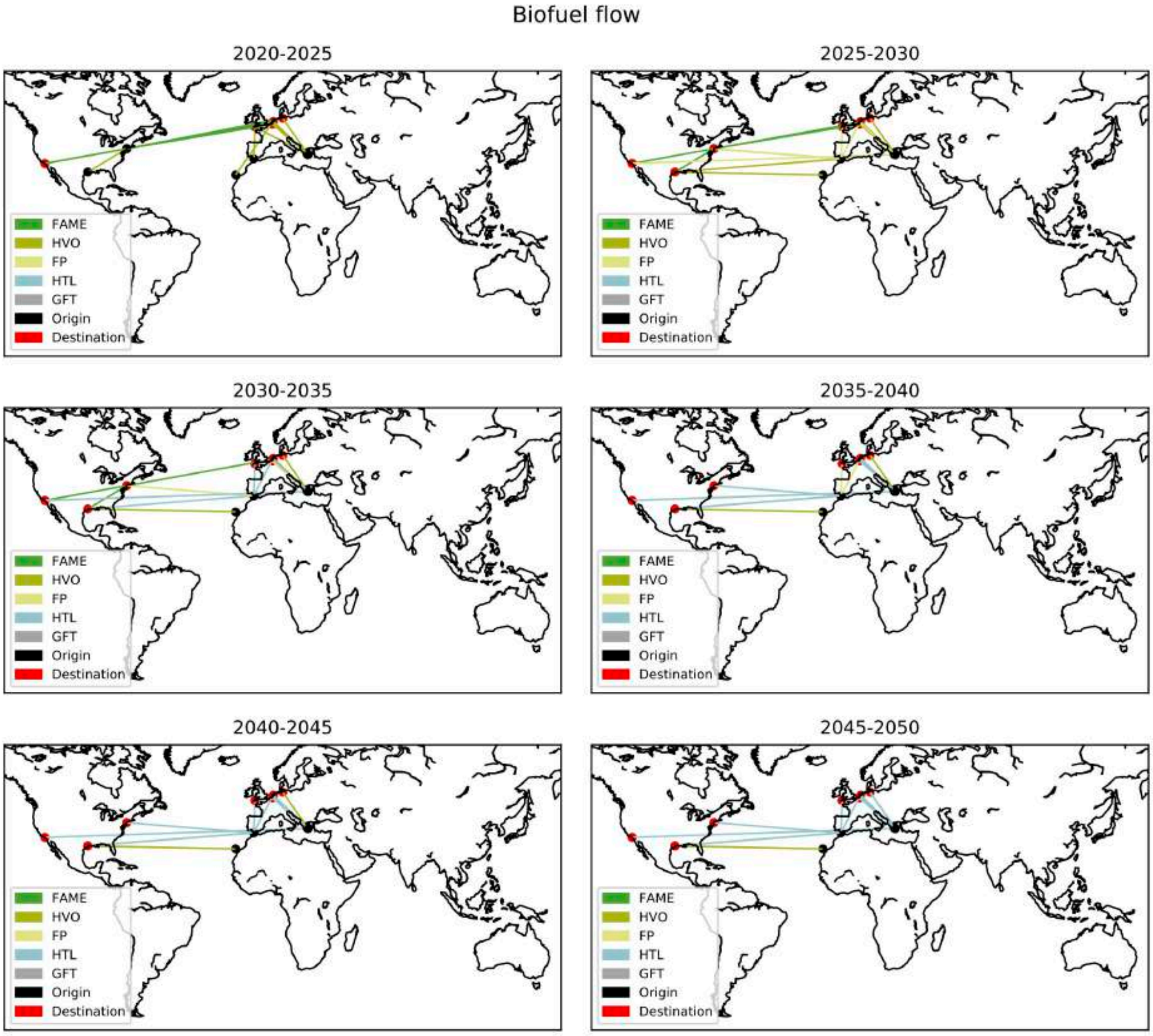

Figure 8.10: Flow of biofuel in between nodes.

There is some trade development between Northern America and Europe. Mostly, upgraded bio-crude is transported from the new advanced bio-refineries in Europe. This indicates that producing these biofuels in Europe and transporting them to Northern America would be more efficient than building new refineries at the source of the demand.

8.4.3. System costs and emissions

From the calculated system flows and investment decisions, which were discussed in the previous section, the total system costs and GHG emissions can be determined. These results are depicted in figures **??** and **??** respectively.

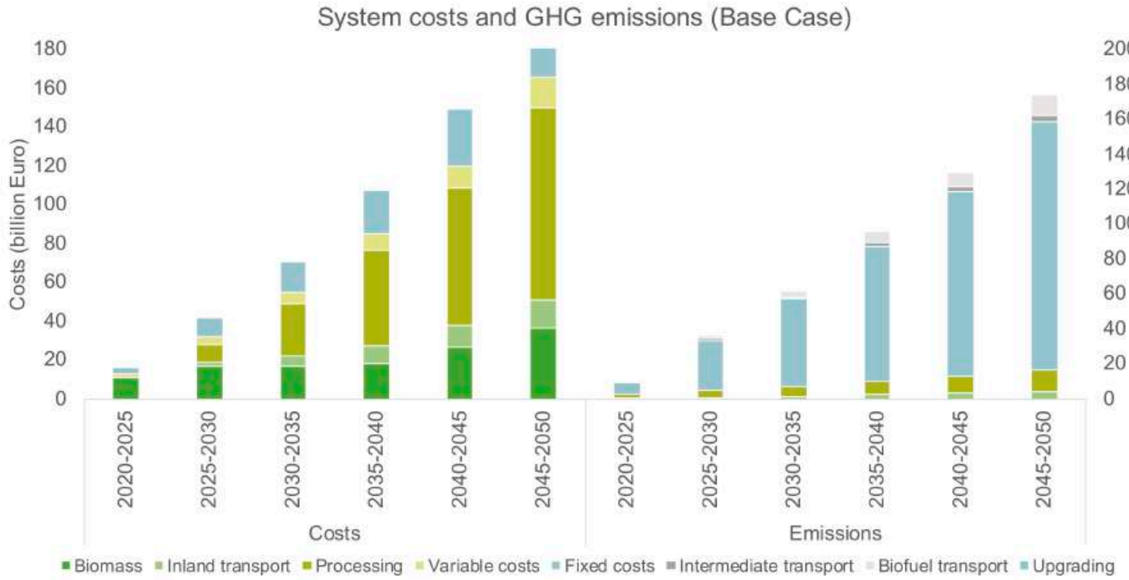

Figure 8.11: Total system costs over the studied period in the example case.

At first, costs are dominated by the cost of waste oils for the production of FAME and HVO. However, over time the costs become significantly more dependent on the processing and upgrading of the new advanced biofuels. This effect is mainly caused by the use of waste streams, which causes the biomass costs to stay relatively constant. The largest cost factor seems the processing of the biomass feedstocks into the intermediate bio-energy carrier.

The total emissions are over the entire period mainly associated with upgrading the intermediate product to the end product. These emissions are largely due to the use of gray hydrogen during the upgrading process. Another contributing factor is the transport of all goods between the ports. However, the share of transport to the overall emissions is small.

8.4.4. Biomass and biofuel deployment

Another interesting element is the optimal use of the different feedstock categories, as shown in figure 8.12. The trade-off between cost reduction and emission reduction is visualized by the selection of waste streams. Local waste and residue streams are used as soon as suitable conversion technologies become available. At the same time, the production of HVO from waste oils is gradually decreased.

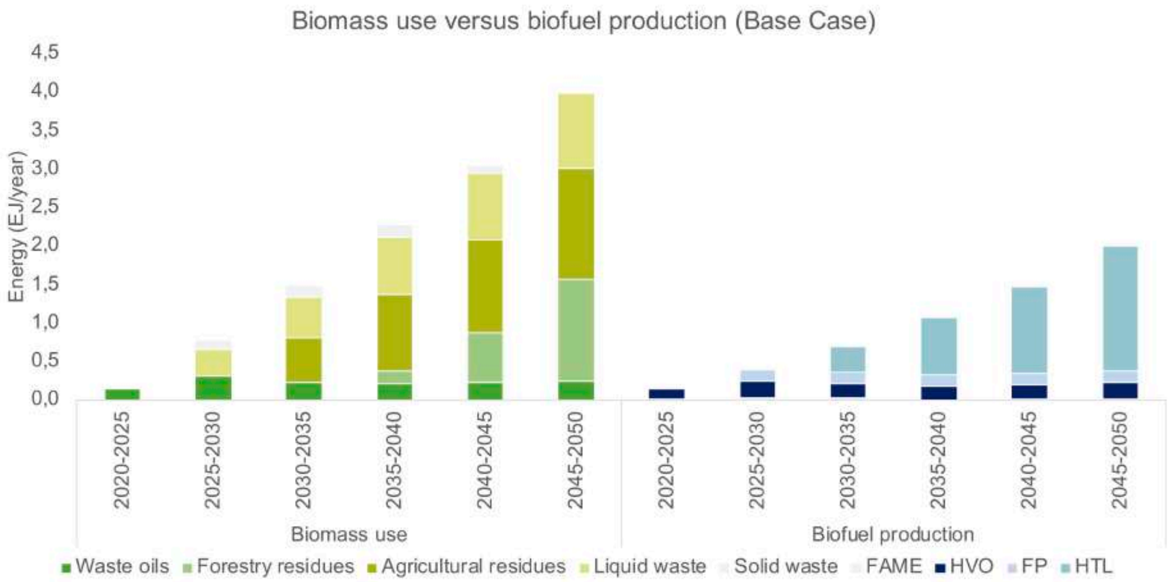

Figure 8.12: Use of biomass and biofuel during the studied period.

The use of biomass is directly linked to the production of the various biofuel types, shown in figure **??**. In the first two time periods waste oils are used to produce HVO, which is replaced by upgraded bio-crude via HTL.

8.5. Model validation

Besides verification of the model, it should also be validated whether the model corresponds with the pre intended requirements. The pre intended model requirements were stated as follows:

"***Model that can optimize the available biomass feedstock, production, transport and port of selling, both for costs and emissions.***"

The developed model satisfies these requirements, optimizing intermediate/biofuel flows and refinery locations in between ports while taking feedstock, production, and transport costs and emissions into account.

To further validate the model, the results from the base case scenario are compared with existing literature. Comparing the resulting refinery locations and network flows is not possible, seeing that optimization on this spatial scale was not done before. However, the most feasible biomass and biofuel deployment scenarios with associated costs and emissions can be compared to literature sources.

The most similar studies found were from de Jong et al. [43] and Grijpma et al. [70]. de Jong et al. [43] looked at the optimal biofuel deployment in Europe for the aviation industry until 2030. The biofuel deployment mix resulting from the assessment of de Jong et al. [43] was more diverse compared to the one in this thesis. The main reason for this is that de Jong et al. [43] focused on RJF, which is only a small fraction of the total product yields. The contribution of fast pyrolysis and HTL were marginal in the study of de Jong et al. [43] were marginal, which is a result of the low specific RJF yields. In contrast to this study, de Jong et al. [43] found gasification Fischer-Tropsch to be one of the more preferred technologies, which was mainly caused by its high RJF yield. Therefore, it could be argued that gasification FT would be more suitable as a fuel for the aviation industry. de Jong et al. [43] indicated average life-cycle GHG emission reduction of 77%-79% compared to fossil fuels. These numbers are in line with the marginal costs of GHG reduction presented in figure 8.6.

Grijpma et al. [70] looked into the shipping sector of Europe and the Netherlands. He did not make a distinction between different advanced biofuel pathways but indicated this as one category. Although the spatial scope of his study is different, general trends can be compared. In contrast to this study, Grijpma et al. [70] took the double-counting of advanced biofuels into account, which drastically decreases the demand for biofuels, seeing that less is required to reach the share of renewables in the transport mix. When taking this effect into account, the distribution of conventional and advanced biofuels in the mix by 2030 is comparable to this study.

Table 8.2: Comparison of results with other studies.

Item	Unit	This study	de Jong et al. [42]	Grijpma et al. [70]
Average biofuel price	EU/ton	900-1200	1258-1522 (Values for RJF)	748-924
Expected distribution between o&f based and advanced biofuels (in 2030)	%	Oils & fat based: 10% Advanced: 90%	Oils & fat based: 15% Advanced: 85%	Oils & fat based: 20% Advanced: 80%
Total emission reduction of marine due to biofuel deployment (2025-2030)	Mt CO2-eq/year	89,5	66	35-40
Average emission per unit of fuel	%	70%-95%	77%-79%	-
Dominant technology	-	HVO/HTL	ATJ/HEFA	Advanced biofuels

9 Scenario analysis

This chapter contains an in-depth analysis of the supply and demand scenarios that were described in chapters 5 and 6. All developed scenarios are used as input to the optimization model which was developed in chapter 4. The results from running these scenarios will help to state an answer to the last sub research question.

What are the most feasible future bio-refinery locations and what is the required regional capacity?

In the first section, a feasibility check will be performed. Consequently, results from Europe, ML, and World scenarios are analyzed both for the low and high supply scenarios. Within each section, the remaining demand and supply scenarios are discussed. At the start of each section, a marginal cost curve is displayed to find the appropriate weight factors for the studied objectives. Abbreviations for the indication of supply and demand scenarios are used. LS and HS stand for low supply and high supply scenario. LD, BD, and HD are associated with the low, base, and high demand scenarios. Lastly, in section 9.5 the results from the scenario analysis are compared to visualize the influence of these scenarios on the costs, emissions, and spatial distribution of the most optimal refinery locations and trade flows.

9.1. Feasibility of scenarios

In table 9.1, a summary of the developed scenarios is provided. If demand exceeds supply, the model becomes infeasible. Before running the various scenarios, it can already be identified whether the model is feasible or not. From chapter 5, it became evident that the availability of oils and fats for the production of FAME and HVO is limited. Therefore, it can be observed that there is a bottleneck in the first period (2020-2025), in which oils and fats are the only feedstocks that are available for the production of biofuels. In figure 9.1, the demand for biofuel and the supply of oils and fats in the first period are visualized for all demand and supply scenarios. It is evident that for the LS scenario, neither of the proposed demand scenarios can be fulfilled. For the HS scenario, only the global IMO targets can not be achieved.

To still achieve the targets, some of the proposed admixture rates in chapter 6 are adjusted. Since the bottleneck is found in the first period, the admixture rates are only adjusted for this period. When more advanced conversion technologies become available, the biomass supply potential becomes significantly larger. The adjusted admixture rates are visualized in table 9.2.

Table 9.1: Description of supply and demand scenarios used in this study.

Geographical scenario	Supply scenario	Demand scenario
Europe European ports comply with the RED II target of 14 % renewable fuel in their transport mix by 2030 as if shipping was included into this target. Double counting mechanisms are not considered. A linear trend is assumed, reaching up until 2050.	**Low Supply (LS)** The LS scenario contains a conservative estimation on biomass feedstock availability combined with significant competition from other industries.	**Low Demand (LD)** The LD scenario uses scenario 11 of the Third GHG Study of the IMO.
Most Likely (ML) Leading countries in sustainability (USA, The Netherlands, Germany, Canada and the UK) are assumed to follow the RED II targets.	**High Supply (HS)** The HS scenario contains a more optimistic view on biomass feedstock availability that would be available for the production of marine biofuels. The road sector is expected to electrify at a fast pace, causing lower competition for certain biomass feedstocks.	**Base Demand (BD)** The BD scenario uses scenario 8 of the Third GHG Study of the IMO.
World All ports are assumed to achieve the IMO target of 50% GHG reduction by 2050 compared to 2008 levels.		**High Demand (HD)** The HD scenario uses scenario 14 of the Third GHG Study of the IMO.

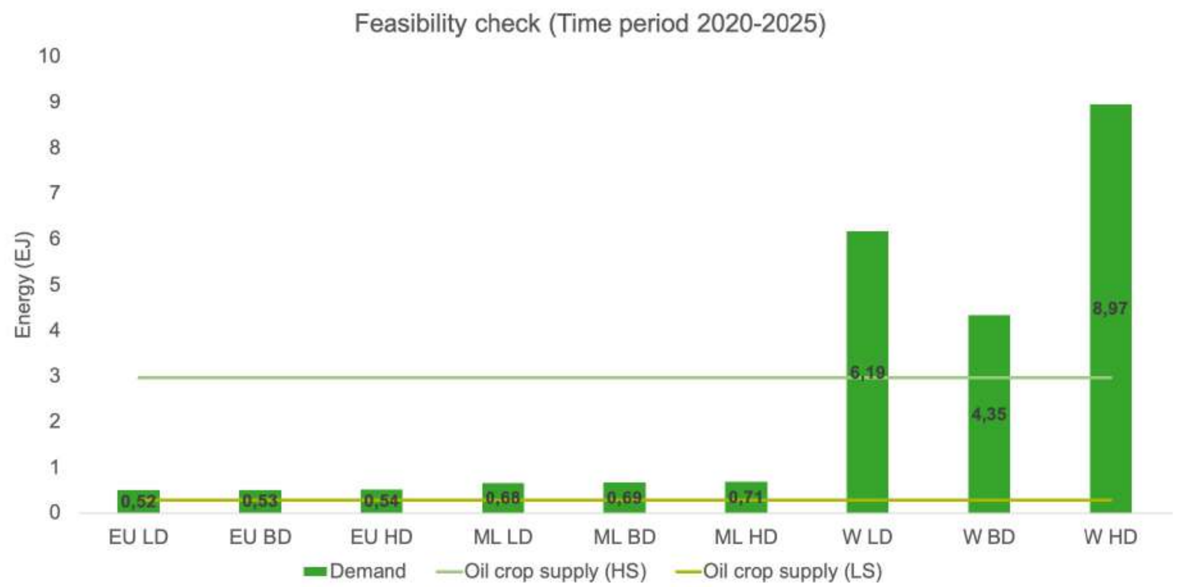

Figure 9.1: Comparing supply and demand between scenarios for the first period (2020-2025). The depicted supply only includes oils and fats.

Table 9.2: Used admixture rates for all scenarios. Rates before adjustment are shown between brackets.

			2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Europe	**Low supply**	**Low**	2.3% (4%)	11%	18%	25%	32%	39%
		Medium	2.3% (4%)	11%	18%	25%	32%	39%
		High	2.2% (4%)	11%	18%	25%	32%	39%
	High supply	**Low**	4%	11%	18%	25%	32%	39%
		Medium	4%	11%	18%	25%	32%	39%
		High	4%	11%	18%	25%	32%	39%
Most-likely	**Low supply**	**Low**	1.8% (4%)	11%	18%	25%	32%	39%
		Medium	1.7% (4%)	11%	18%	25%	32%	39%
		High	1.7% (4%)	11%	18%	25%	32%	39%
	High supply	**Low**	4%	11%	18%	25%	32%	39%
		Medium	4%	11%	18%	25%	32%	39%
		High	4%	11%	18%	25%	32%	39%
World	**Low supply**	**Low**	0.6% (13%)	24%	33%	39%	43%	44%
		Medium	0.6% (9%)	22%	38%	54%	65%	77%
		High	0.6% (18%)	33%	51%	69%	83%	93%
	High supply	**Low**	6% (13%)	24%	33%	39%	43%	44%
		Medium	6% (9%)	22%	38%	54%	65%	77%
		High	6% (18%)	33%	51%	69%	83%	93%

Especially for the scenarios which are based on the IMO targets, the admixture rate is severely decreased. In the following sections, the results from the developed scenarios are analyzed.

9.2. Europe

As stated in section 6.2.1, the Europe scenario looks at the biofuel deployment required to reach the RED II targets for the transport sector. Shipping is at this stage not included in these targets. However, the purpose of this study is to look into these regulatory frameworks as if shipping were included. The scenarios studied in this section are indicated in figure 9.2.

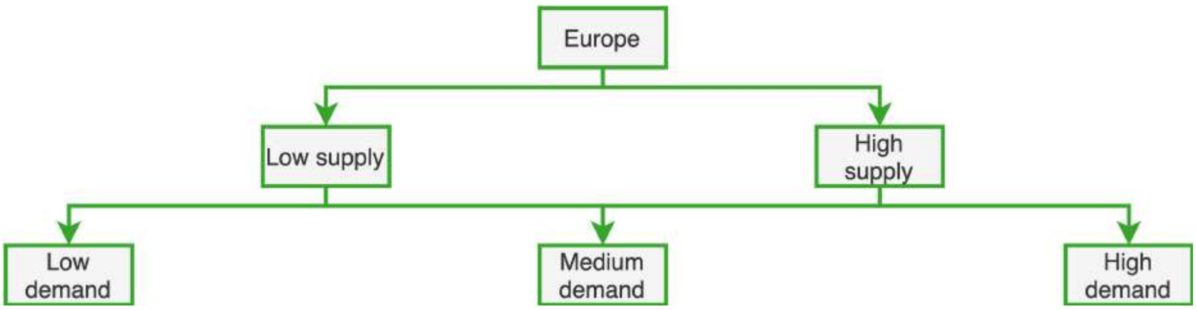

Figure 9.2: Studied combinations of Europe scenarios

The following subsections elaborate on the most feasible trade flows, refinery locations, biomass/biofuel deployment and associated costs and GHG emissions. Subsections 9.2.1 and 9.2.2 study the European scenario combined with the LS and HS scenarios respectively.

9.2.1. Europe Low Supply (LS) scenario

In the European LS scenario, the low biomass supply scenario is combined with the European demand scenario. This entails a demand for biofuels in European ports while a conservative amount of available biomass is assumed. Firstly, a marginal cost curve is developed for the Europe LS scenario, to find the desired trade-off between costs and emissions. This curve is depicted in figure 9.3. The most feasible trade-off is found to be achieved with a weight factor of 0.35 and 0.75 for the environmental and economic objective respectively. This corresponds to an average fuel cost of 955 EU/ton and a 78.9 % GHG reduction compared to HFO.

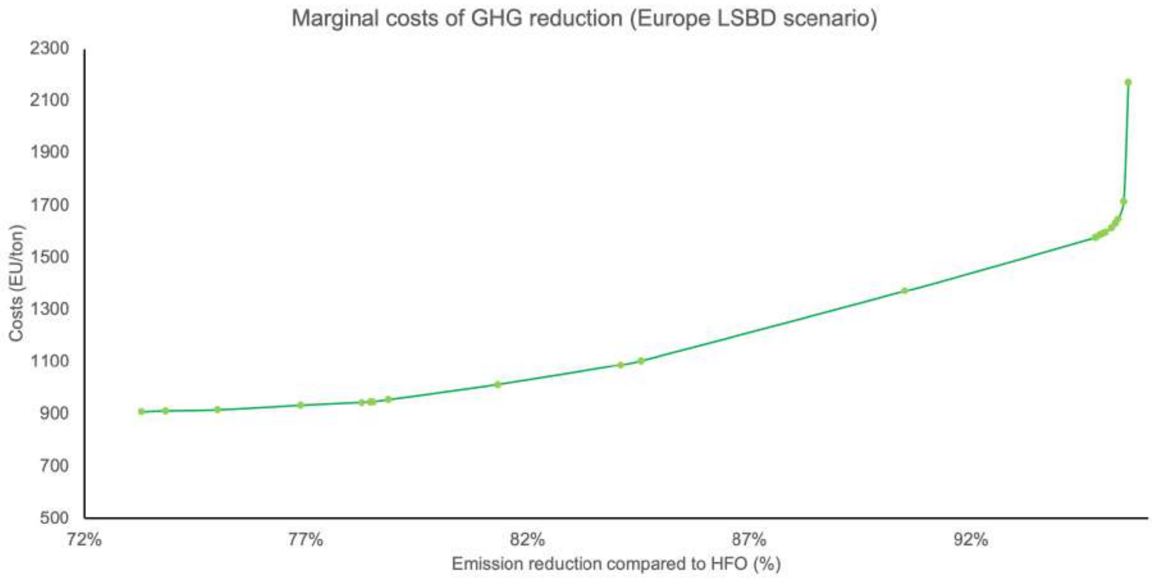

Figure 9.3: Marginal cost curve for the European low supply scenario

The three different energy demand scenarios (LD, BD and HD) will be visualized side by side, to clarify the influence of growing energy demand from the shipping sector on required biofuel supply. The resulting refinery locations and trade flows are only shown for the Base Demand (BD) scenario. The different colors of the trade flows, indicate which commodity is shipped. The black and red nodes indicate origin and destination nodes respectively. A node is also colored red when intermediate products are supplied internally. The drawn trade flows do not identify the route that is sailed, but solely connect the origin and destination.

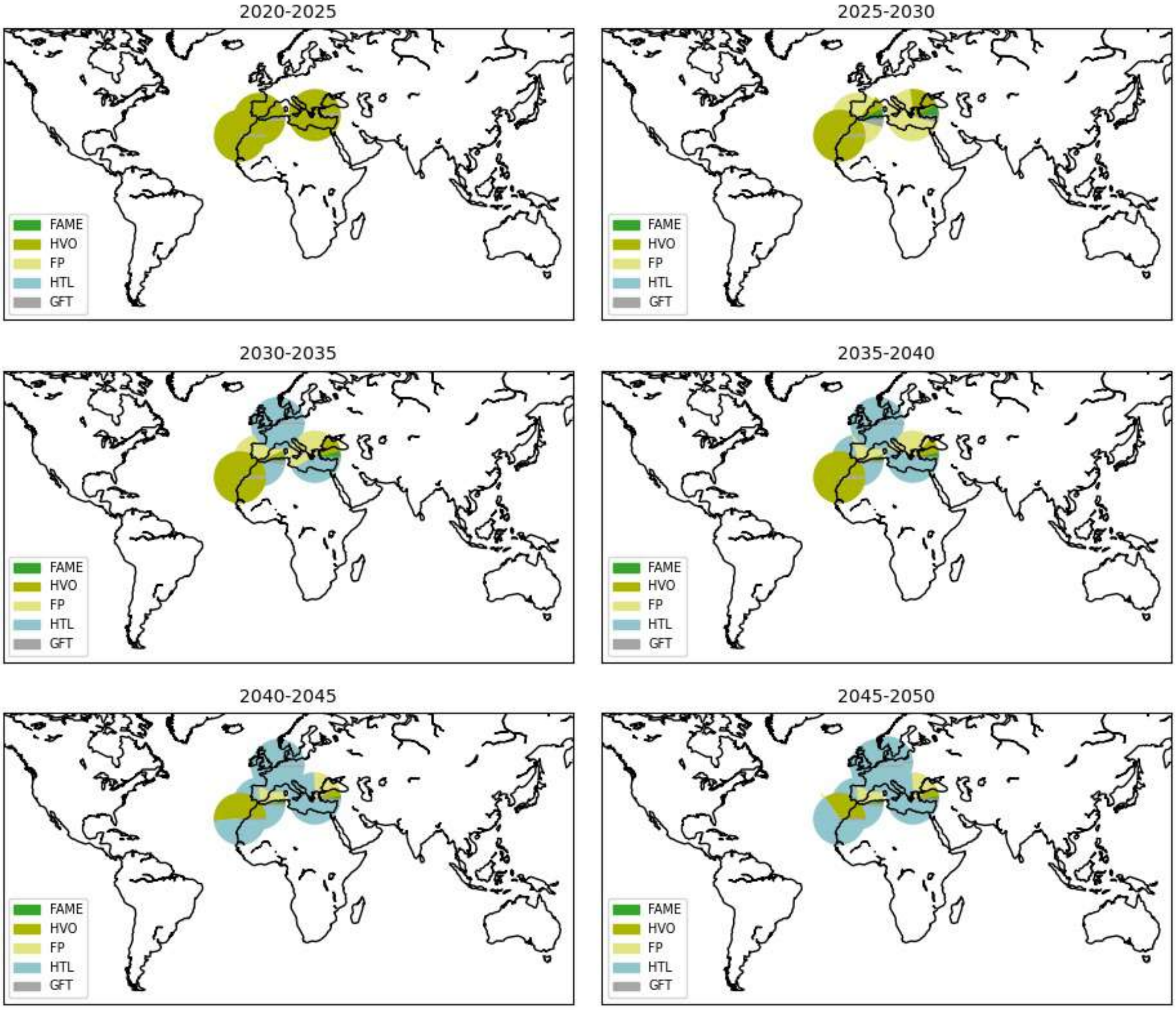

Figure 9.4: Optimal bio-refinery locations for the Europe LSBD scenario.

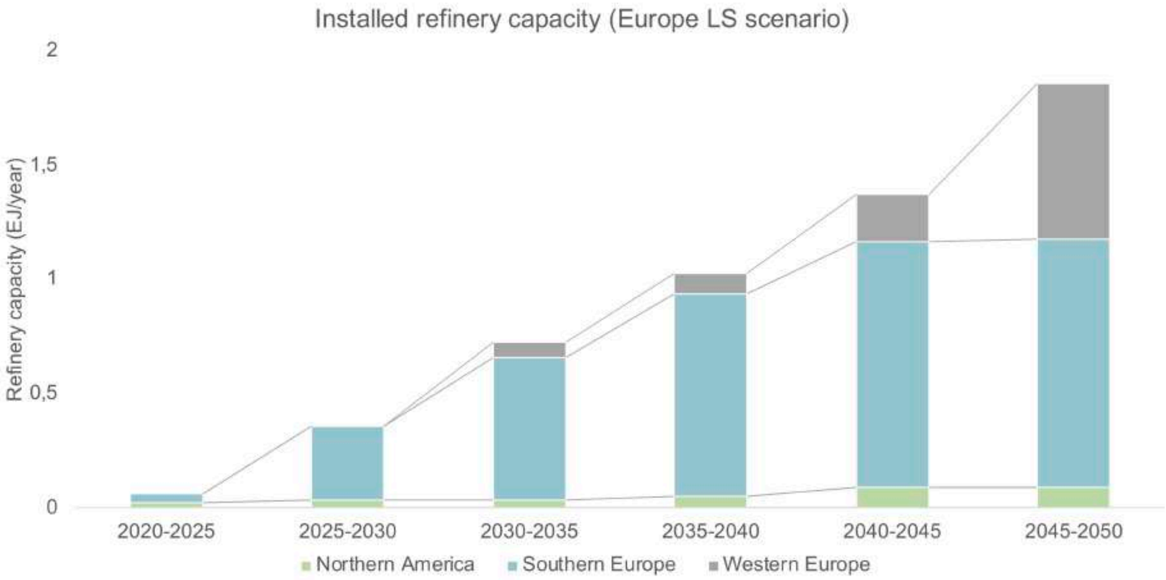

Figure 9.5: Optimal refinery deployment in the European LSBD scenario.

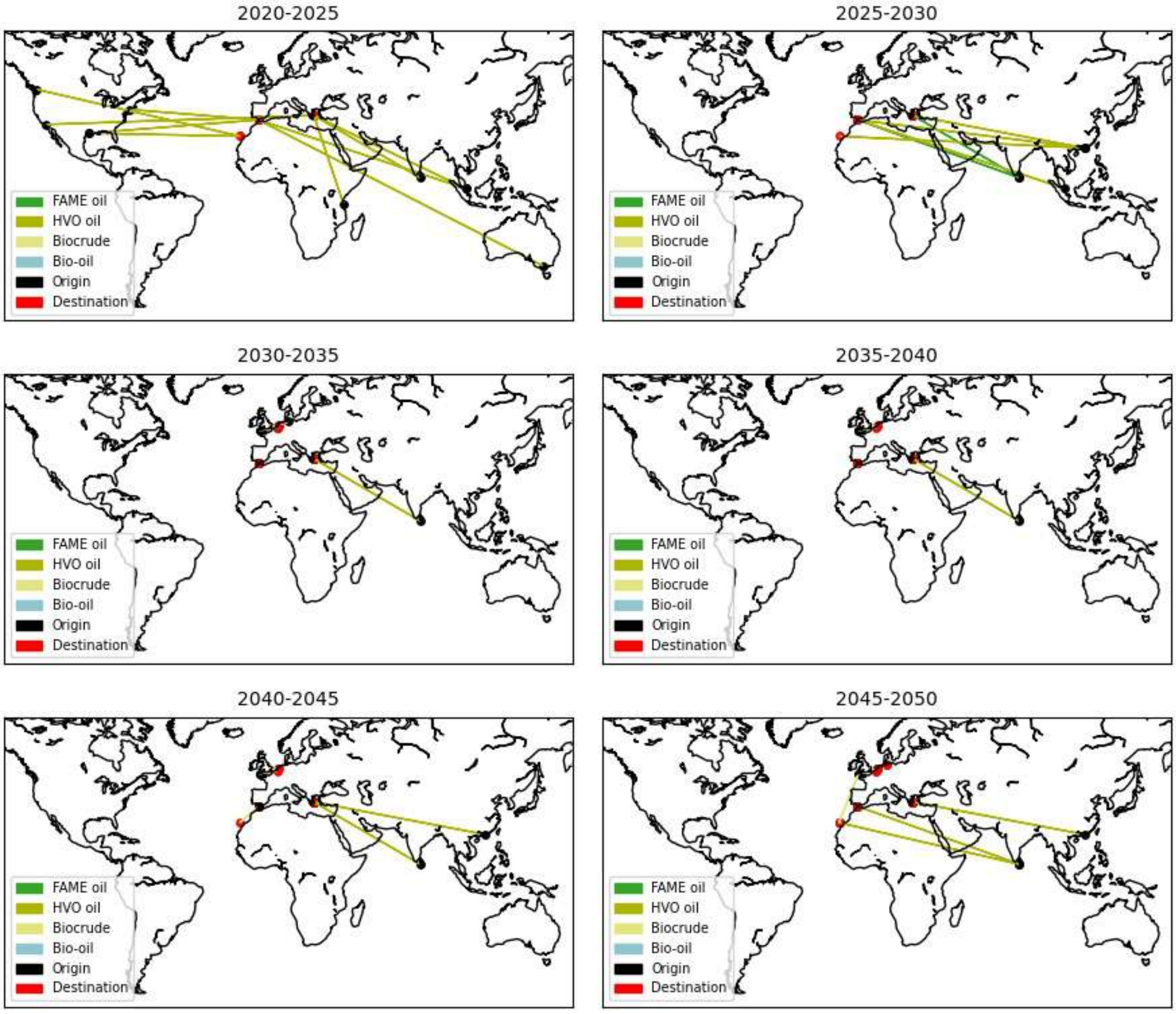

Figure 9.6: Intermediate trade-flows for he Europe LSBD scenario

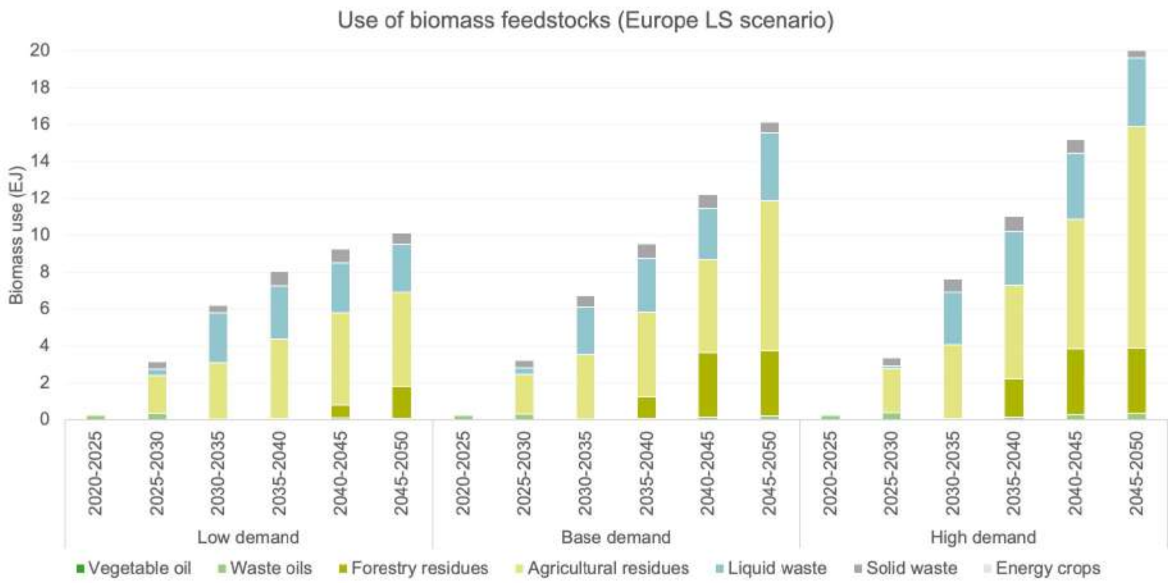

Figure 9.7: Predicted use of biomass for the Europe LS scenario

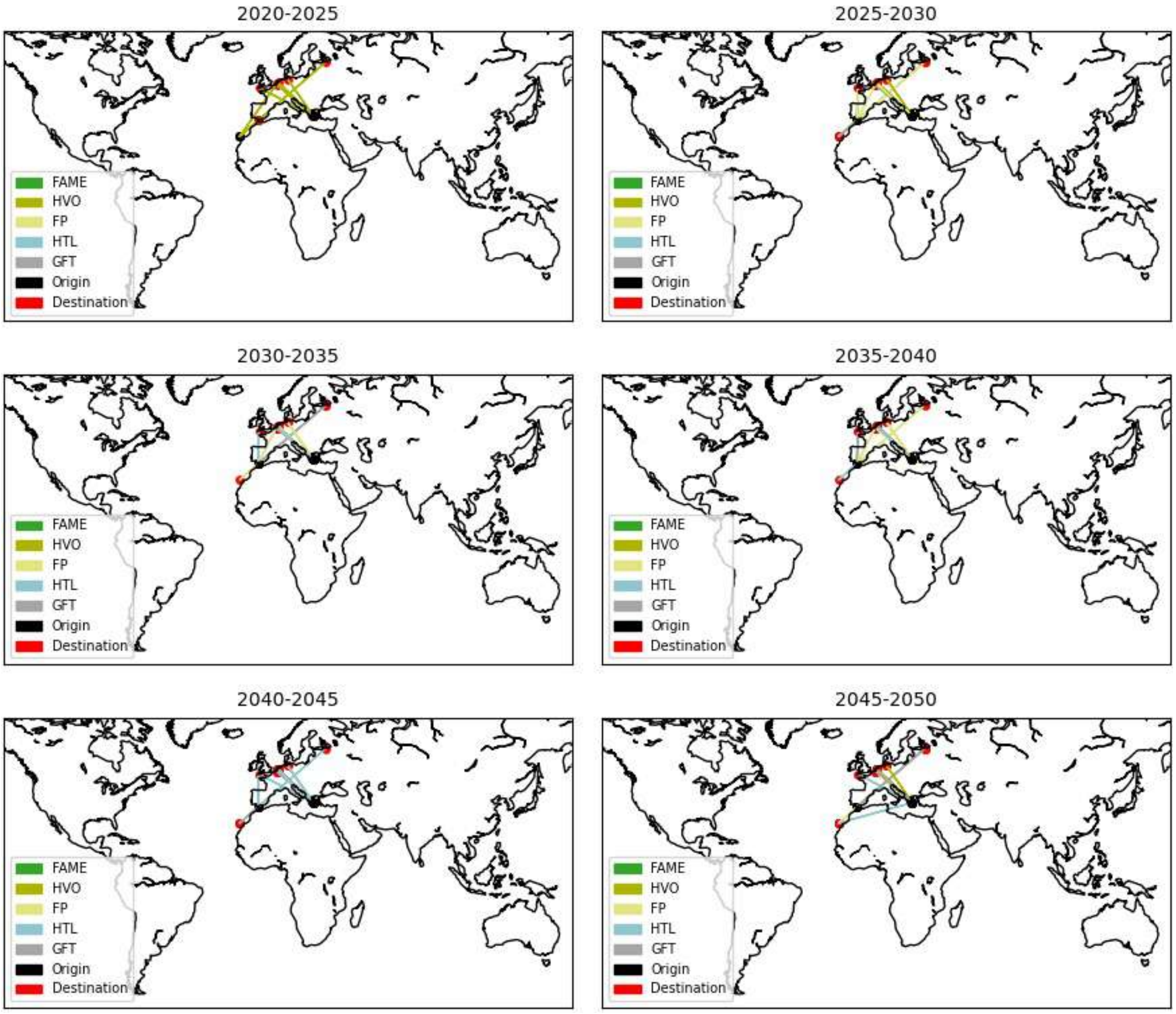

Figure 9.8: Biofuel mobilization in Europe LSBD scenario.

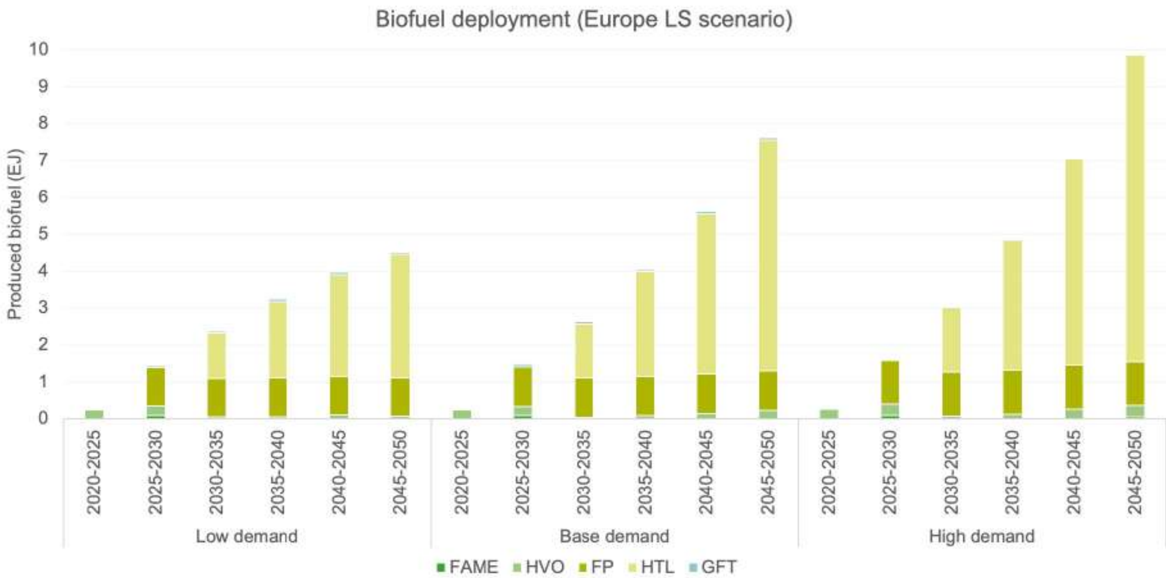

Figure 9.9: Biofuel deployment in Europe LS scenario.

The optimal bio-refinery locations for this scenario were indicated in figure 9.4. The pie charts at the refinery nodes indicate the share in the total refinery capacity represented by the different conversion technologies. For this scenario, the refineries are located near the demand nodes. Hence, transportation of biofuels is only performed inside Europe, reducing the emissions from deep-sea transport. Figure 9.5 shows the expected deployment of biofuels for the maritime industry. Southern Europe is the preferred region for building refineries. Within Southern Europe, the refinery hubs are Pireaus, Las Palmas, and Gibraltar. At first, predominantly HVO is produced in Piraeus. Over time, the share of FP and HTL increases. Eventually, HTL becomes dominantly present in the total biofuel mix. It stands out that Fischer-Tropsch is not included in the biofuel mix in any case. This mainly results from the poor economic performance of Fischer-Tropsch compared to fast pyrolysis and HTL.

The resulting biofuel trade-flows are indicated in figure 9.8. Most of the HVO supply to the European ports originate from the ports in Southern Europe. Although the results indicate that biofuel is only traded within Europe, the intermediate products that serve as a feedstock for biofuel production are initially imported to Europe from Northern America and Asia, which is shown in figure 9.6. The only technologies that are available in the first period are FAME and HVO. Additionally, FAME has a blend-wall of 7% and the use of waste oils is forbidden in this scenario. This results in the import of vegetable oils from Asia at the start of the studied period. After the second time period, the use of HVO and FAME diminishes, which is also shown in figure 9.9. Figure 9.9 indicates that a steady amount of fast-pyrolysis capacity is maintained, while the increasing demand is fulfilled with HTL.

The biomass deployment after the second period exists in a combination of forestry residues, agricultural residues, solid waste, and liquid waste, which is shown in figure 9.7. The most used feedstock appears to be agricultural residues. This can be explained by its large potential availability and strong economic and environmental performance. Solid and liquid waste is also included in the biomass mix. Although the use of these feedstocks induces low unit emissions and costs, the conversion yields are somewhat lower.

In figure 9.10, the total resulting system costs are depicted. The costs are for a significant part related to the intermediate bio-energy carrier. These costs include inland transport, purchasing and processing of the biomass feedstock. The remainder of the expenses are related to fixed and variable costs of setting up and operating new upgrading facilities.

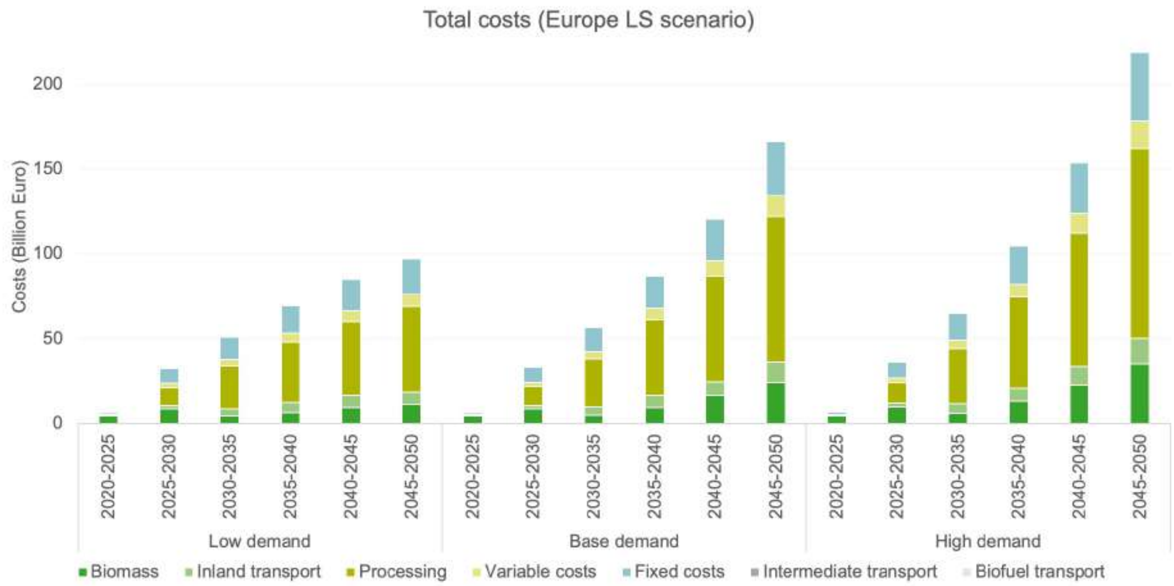

Figure 9.10: Total system costs in the Europe LS scenario.

In figure 9.11, the total system emissions for the various demand scenario are shown. Although upgrading of the intermediate bio-energy carrier is not necessarily the major contributor to the fuel production costs, it is responsible for almost all additional GHG emissions. Like indicated in section 8.2, external purchase of hydrogen is the main cause.

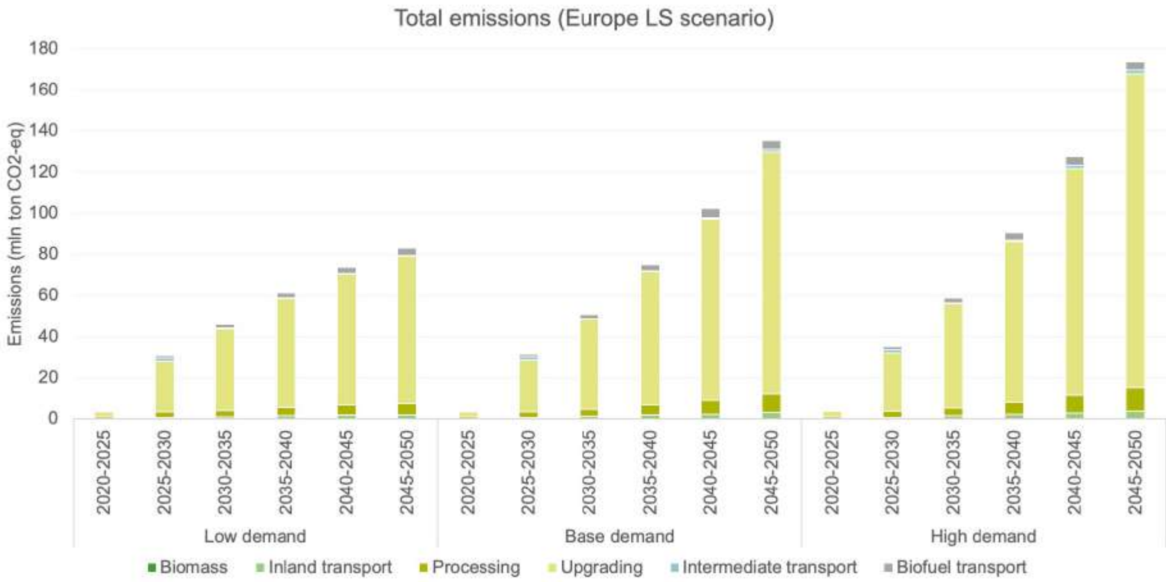

Figure 9.11: Total system emissions in the Europe LS scenario.

9.2.2. Europe High Supply (HS) scenario

In the Europe HS scenario, the same assumptions as in the Europe LS scenario are made, except for the more optimistic estimation of biomass feedstock availability. Especially the increased availability of oils and fats might result in a different solution. A new marginal cost curve is drawn in figure 9.12 to identify the desired trade-off between costs and emissions, which was found to be realized at 78.8 % reduction compared to HFO for an average fuel cost of 943 EU/ton.

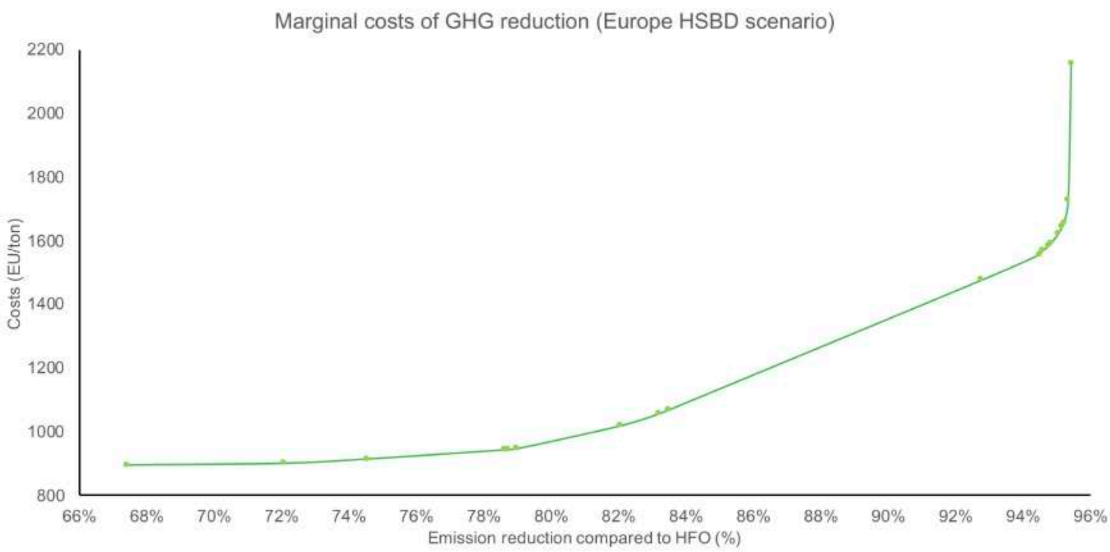

Figure 9.12: Marginal cost curve for the Europe HSBD scenario

Running this scenario results in the solutions depicted in figures 9.13, 9.14, 9.15 and 9.16.

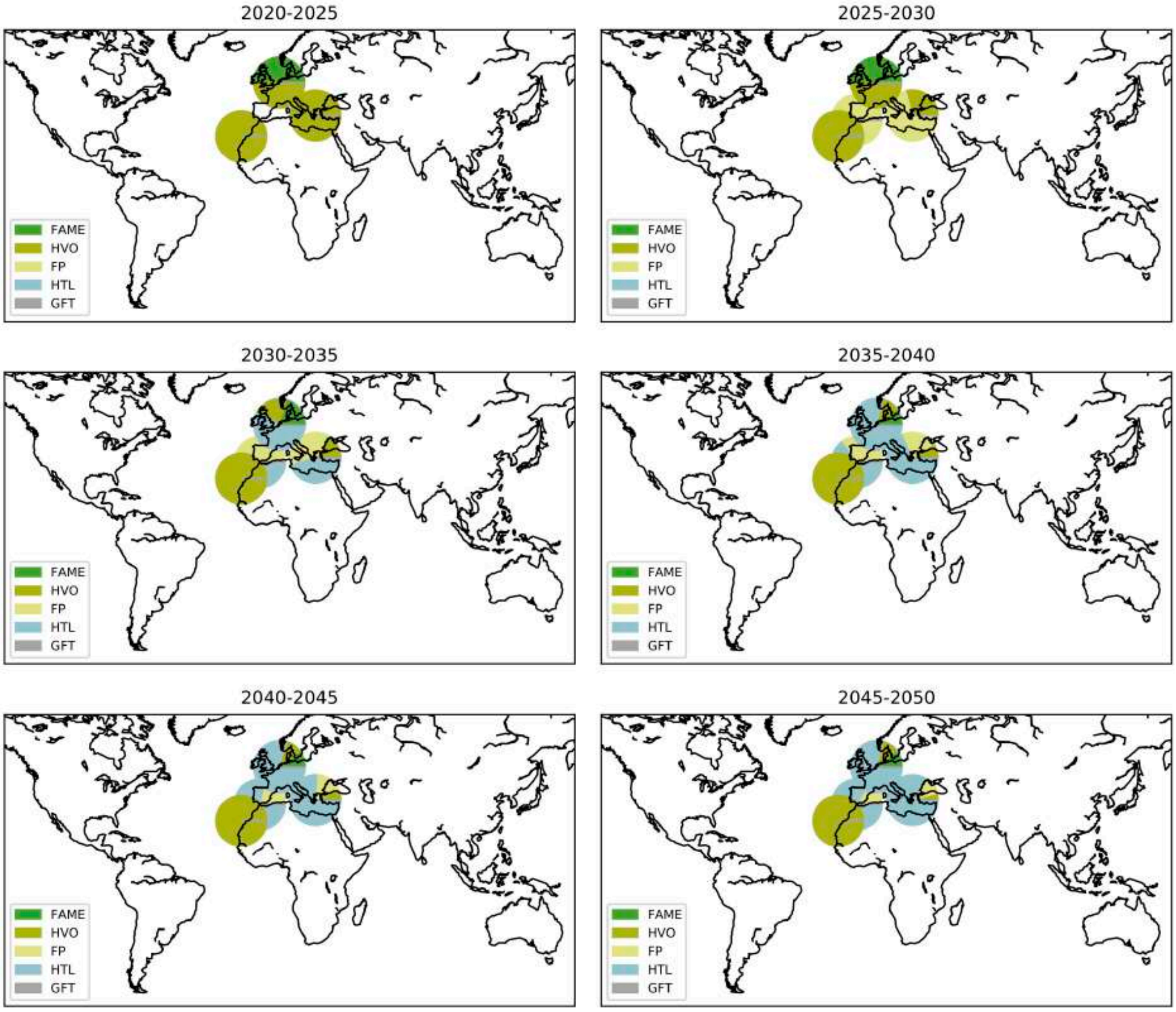

Figure 9.13: Optimal refinery locations for Europe HSBD scenario

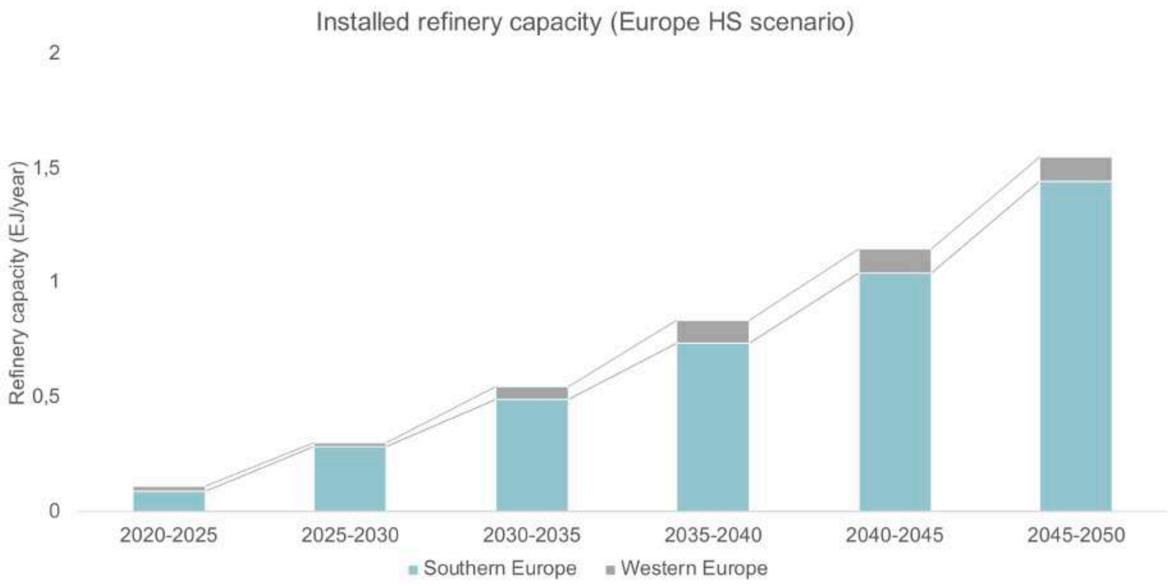

Figure 9.14: Required refinery capacity in Europe HSBD scenario

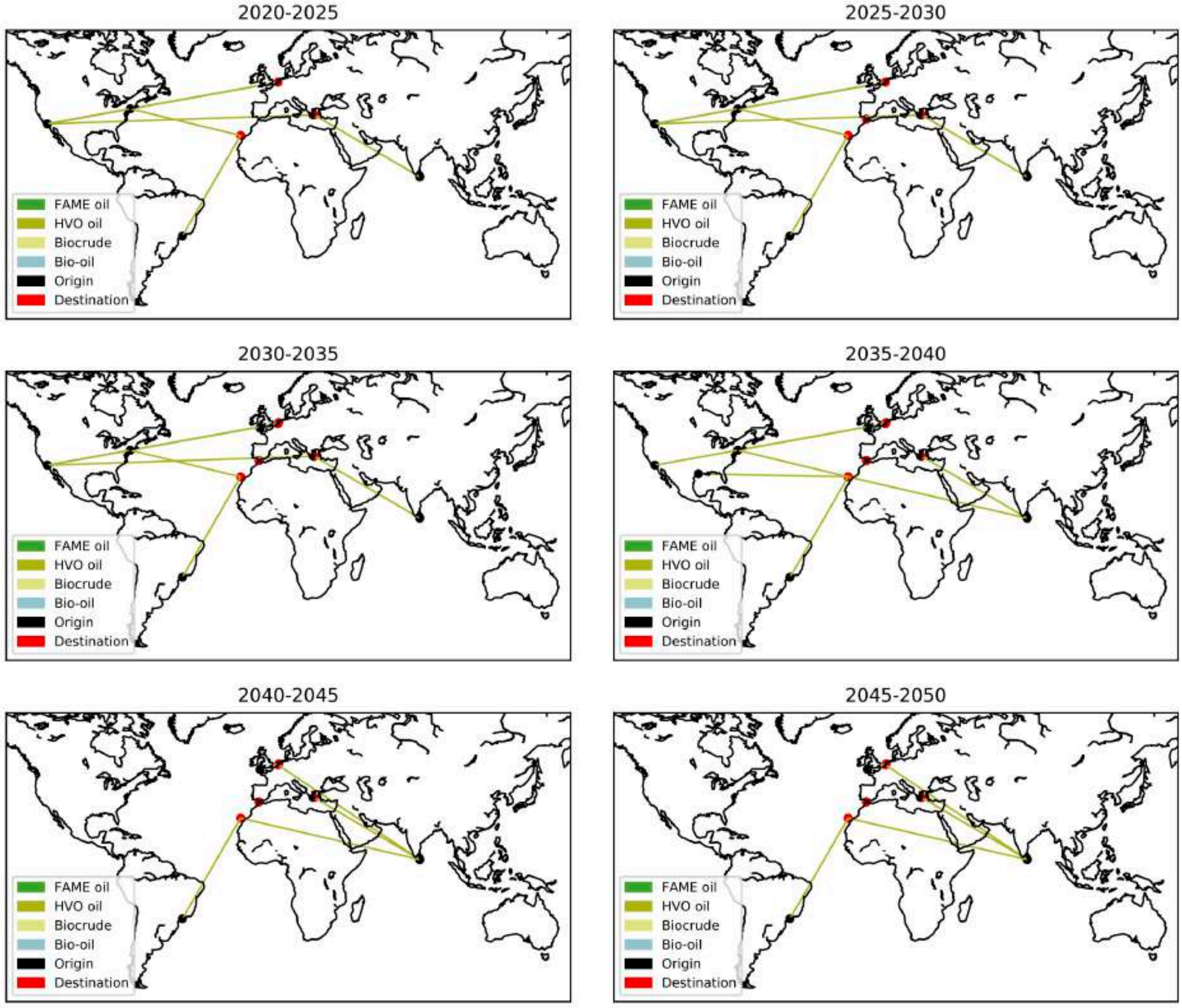

Figure 9.15: Intermediate trade flow for Europe HSBD scenario

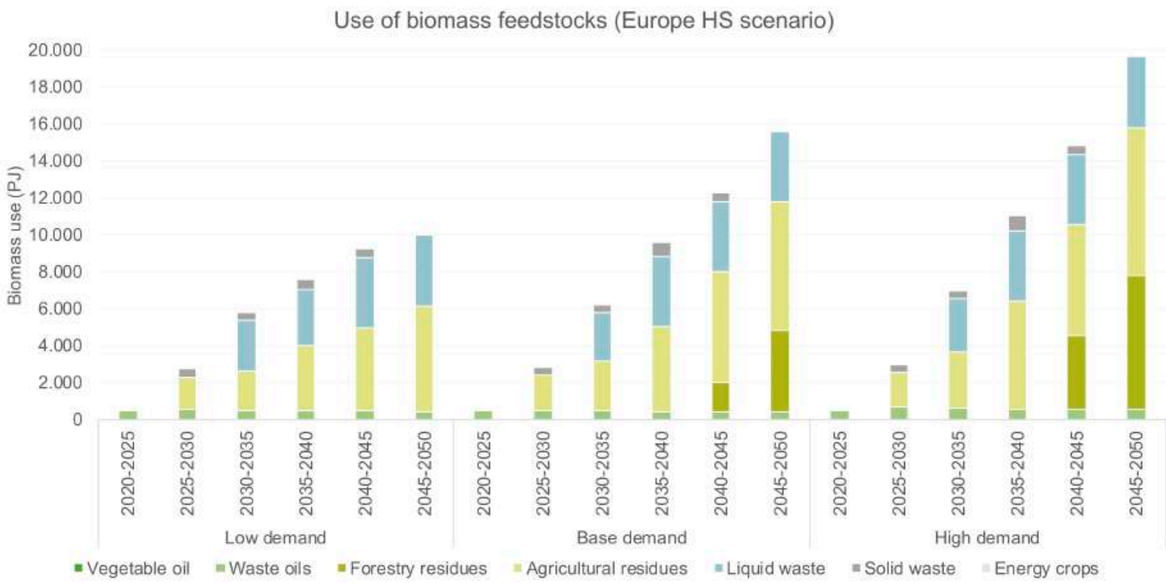

Figure 9.16: Biomass deployment in Europe HS scenario

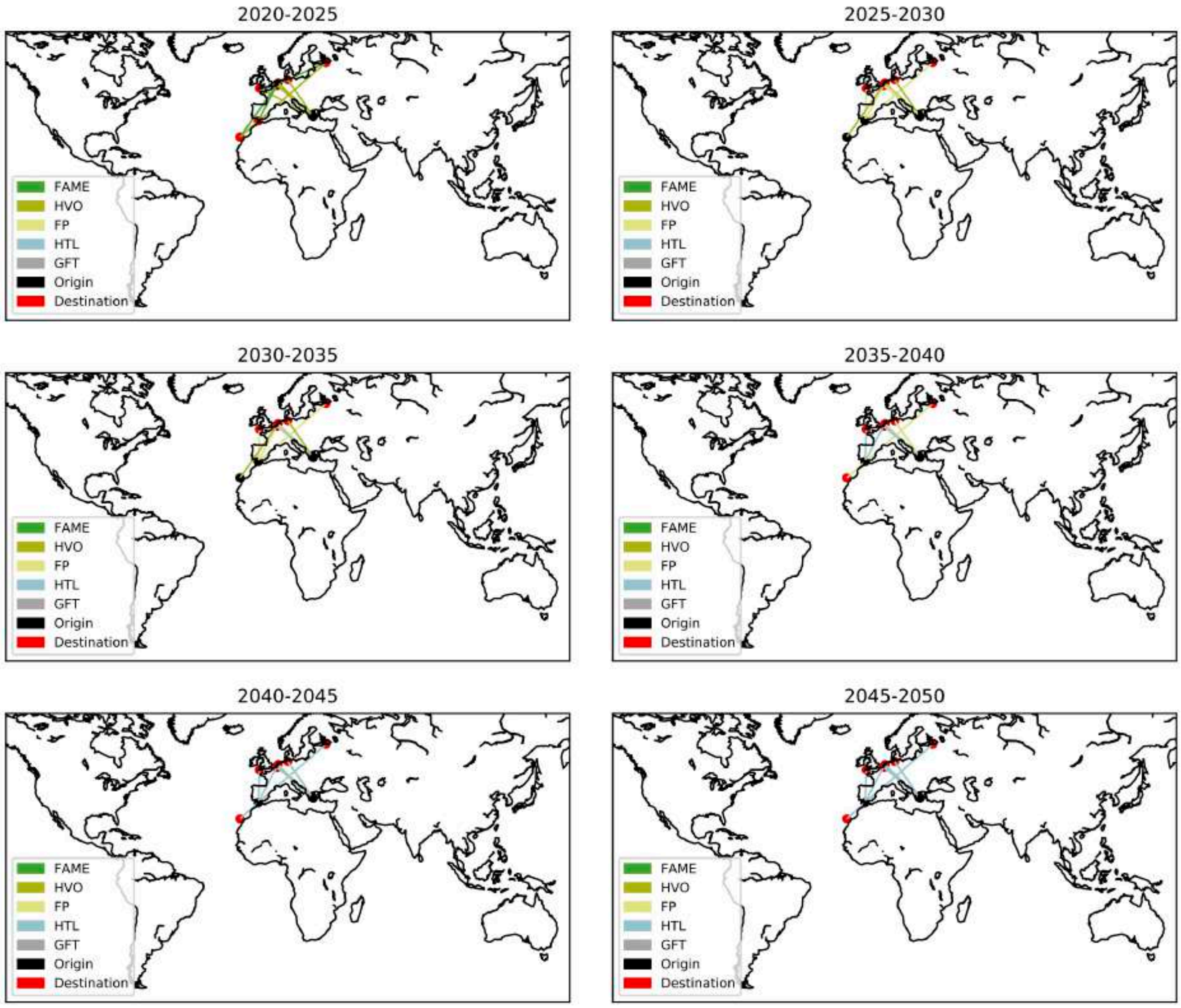

Figure 9.17: Biofuel trade flow for Europe HSBD scenario

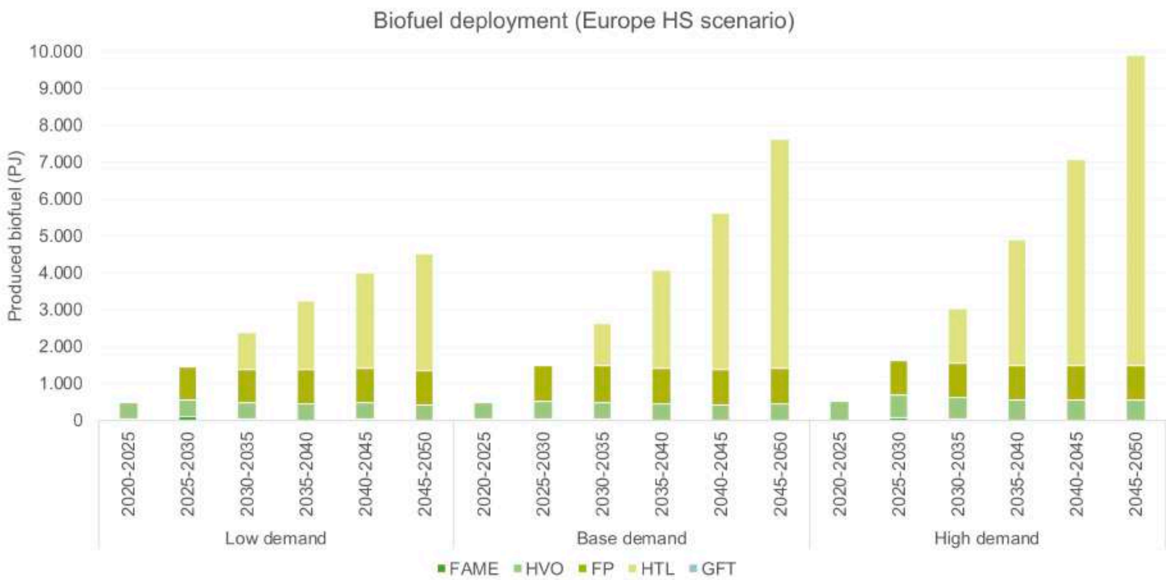

Figure 9.18: Biofuel deployment in Europe HS scenario

From the previous figures, it can be concluded that the influence of increasing biomass supply on the eventual result is not significant. The main difference is the continuous use of the available waste oils and the increase in the production of HVO. These waste oils are imported from Brazil, India and the USA. Although waste oils are used over the entire studied time period, it became evident from figure 9.16 that they are only able to cover a tiny piece of future biofuel demand. Analogous to the Europe LS scenario, HTL is the preferred technology to cover rising biofuel demand. The trade-flows of biofuel are shown in figure 9.17. It can be identified that in the Europe HS scenario, biofuel is also traded mainly inside Europe.

9.3. Most likely

In this section, the scenario in which leading countries in the field of sustainability regulations include shipping in their policies, is studied. This scenario will, in the remainder of this thesis, be indicated as the ML scenario. The following section will cover the ML LS scenario. The Most-Likely HS scenario will not be studied, because this is the Base Case scenario and was already discussed in chapter 8. Within the ML HS section, all different demand scenarios (LD, BD and HD) will also be taken into account. This structure is visualized in figure 9.19.

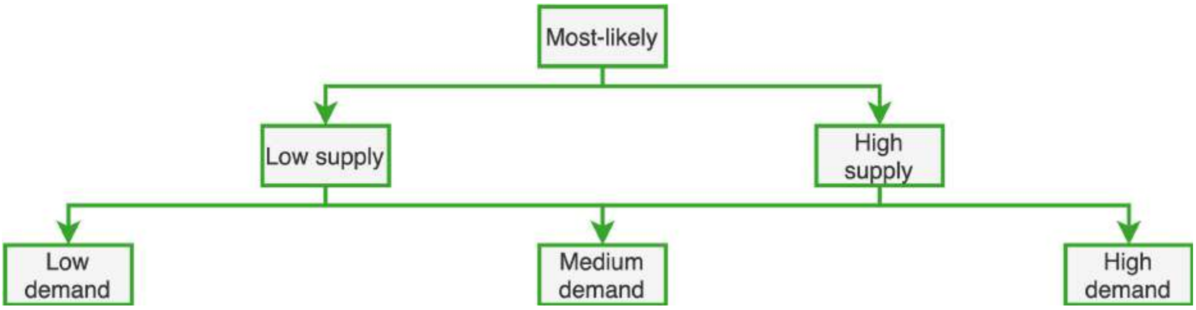

Figure 9.19: Studied combinations for the Most-Likely (ML) scenario.

9.3.1. Most-likely Low Supply (LS) scenario

The Most-likely LS scenario looks into the situation in which leading countries on the front of sustainability make efforts to include shipping in their renewable energy targets. As a proxy, the RED II targets are imposed on the USA, Europe and Canada. This demand scenario is in this case combined with a conservative estimation of biomass availability for the maritime industry.

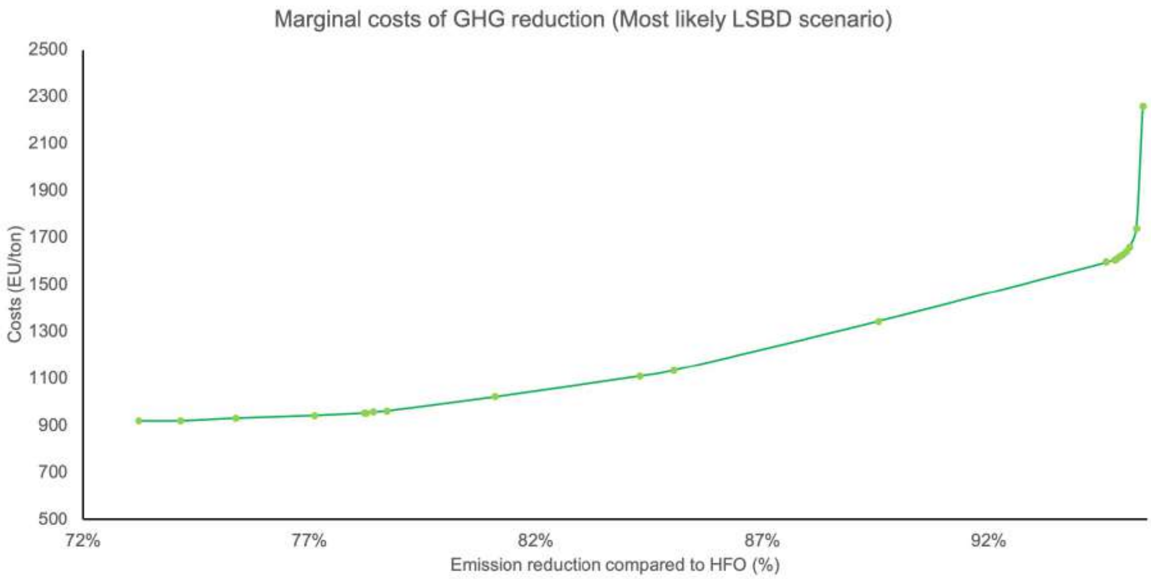

Figure 9.20: Marginal cost curve for ML LSBD scenario.

The marginal costs curve for the ML LSBD scenario is shown in figure 9.20. The best trade-off is found at an average biofuel cost of 959 EU/ton for 77% GHG reduction compared to HFO. Using the associated weight factors, the ML LS scenario is simulated. The trade-flows and refinery locations are only shown for the Base Demand (BD) scenario.

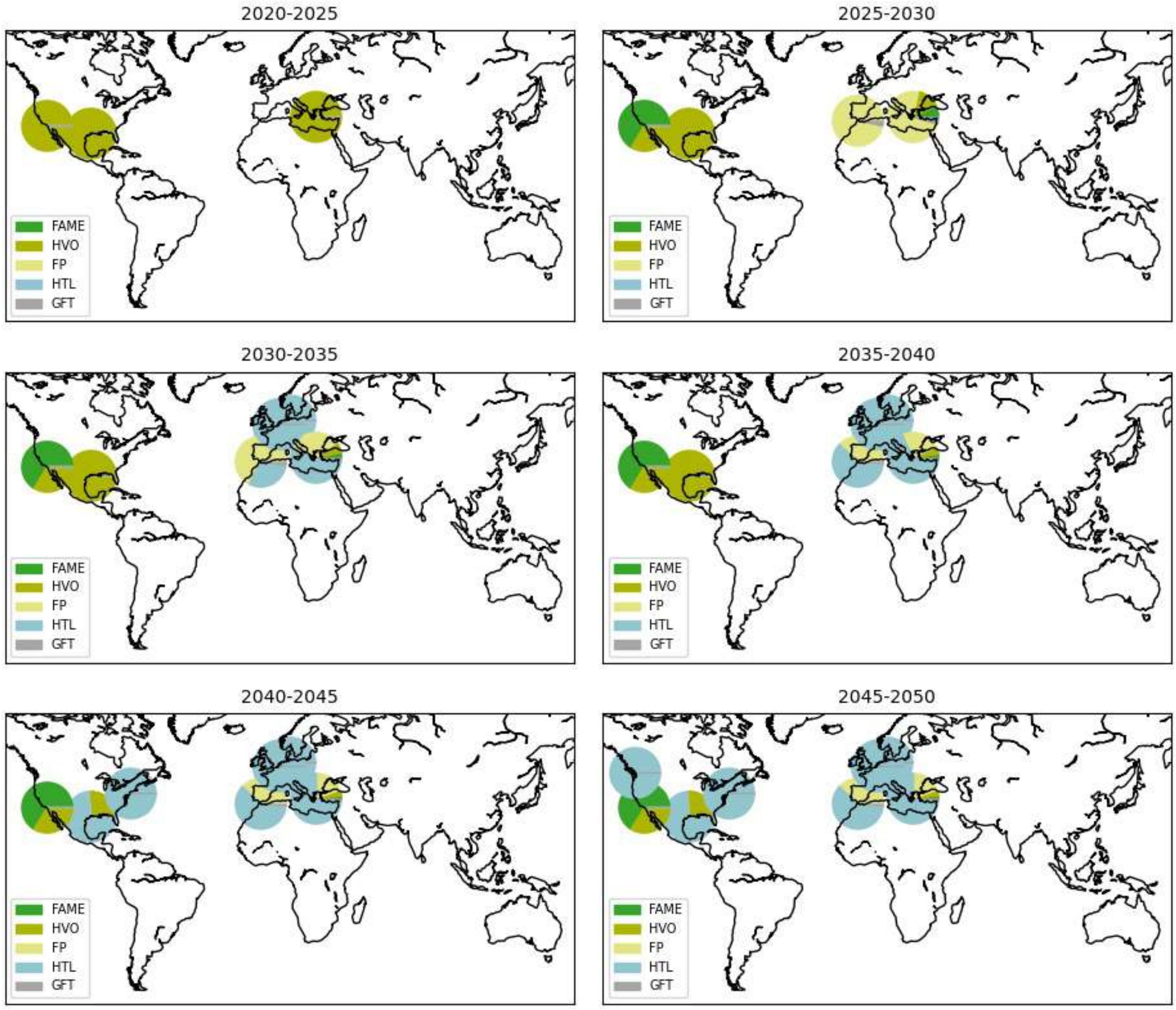

Figure 9.21: Optimal refinery locations for ML LSBD scenario.

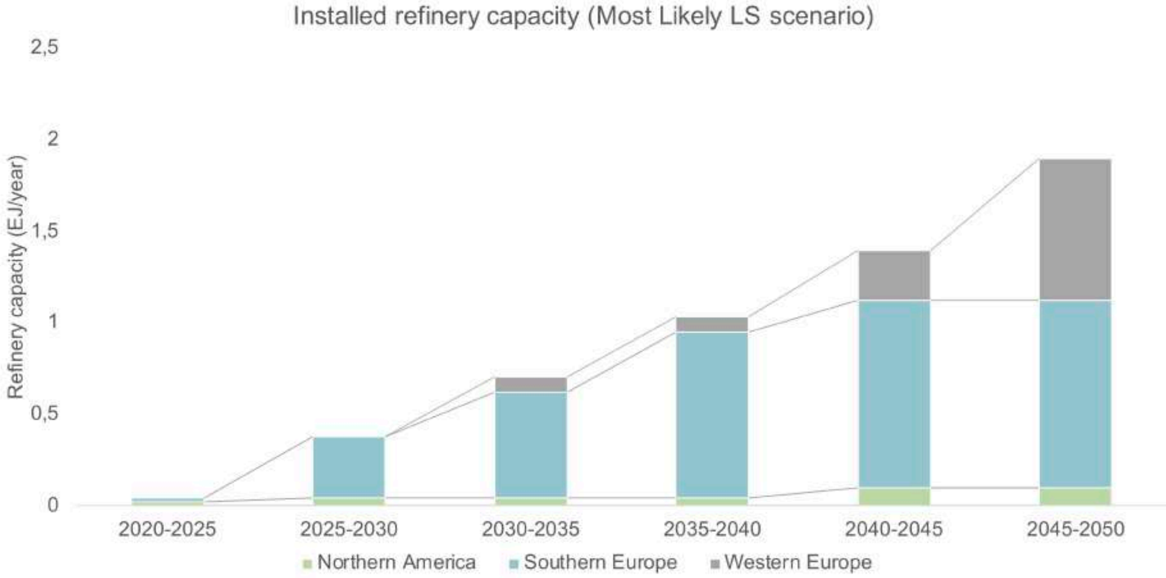

Figure 9.22: Optimal refinery deployment for ML LSBD scenario.

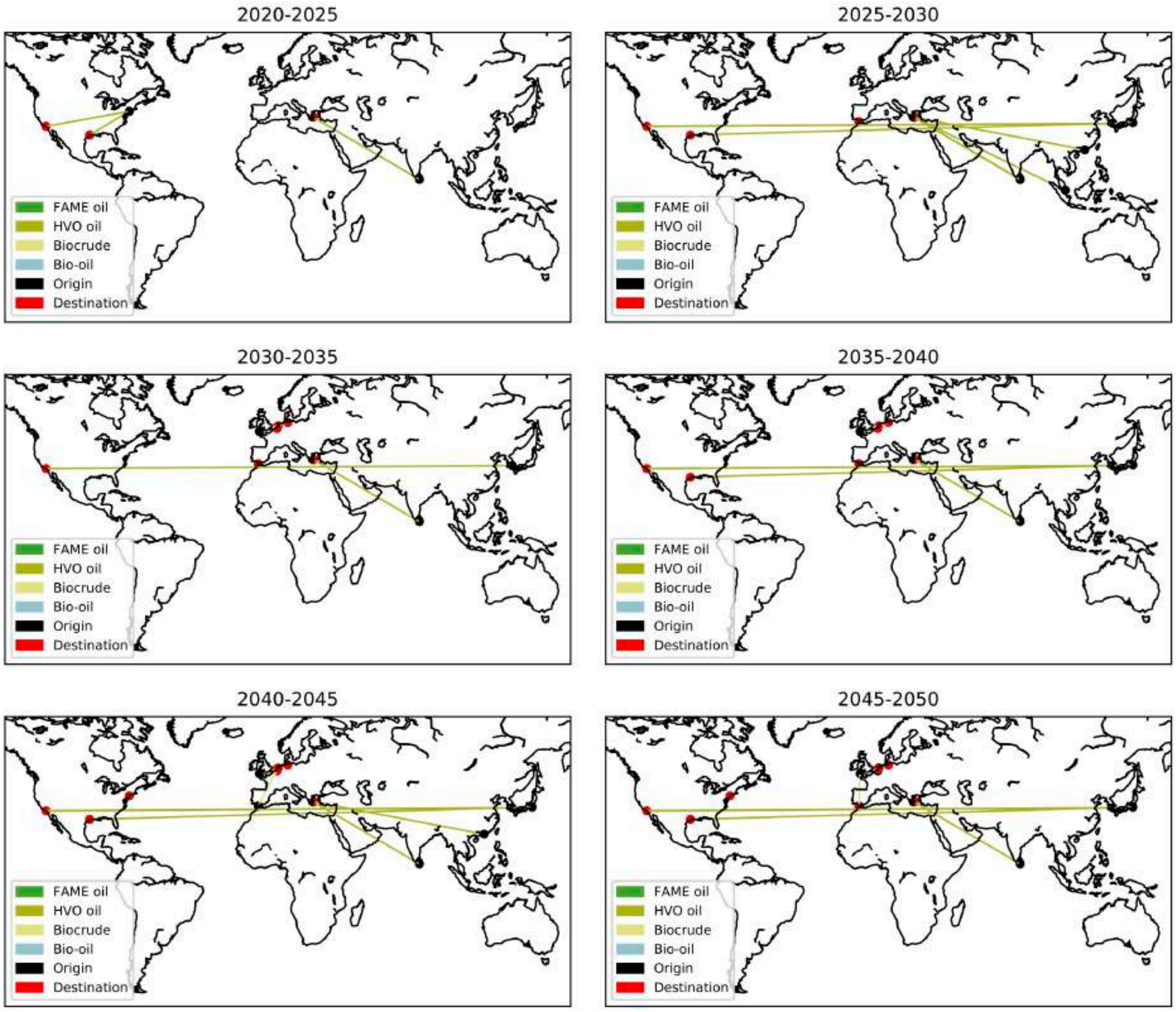

Figure 9.23: Intermediate trade flow in the ML LSBD scenario.

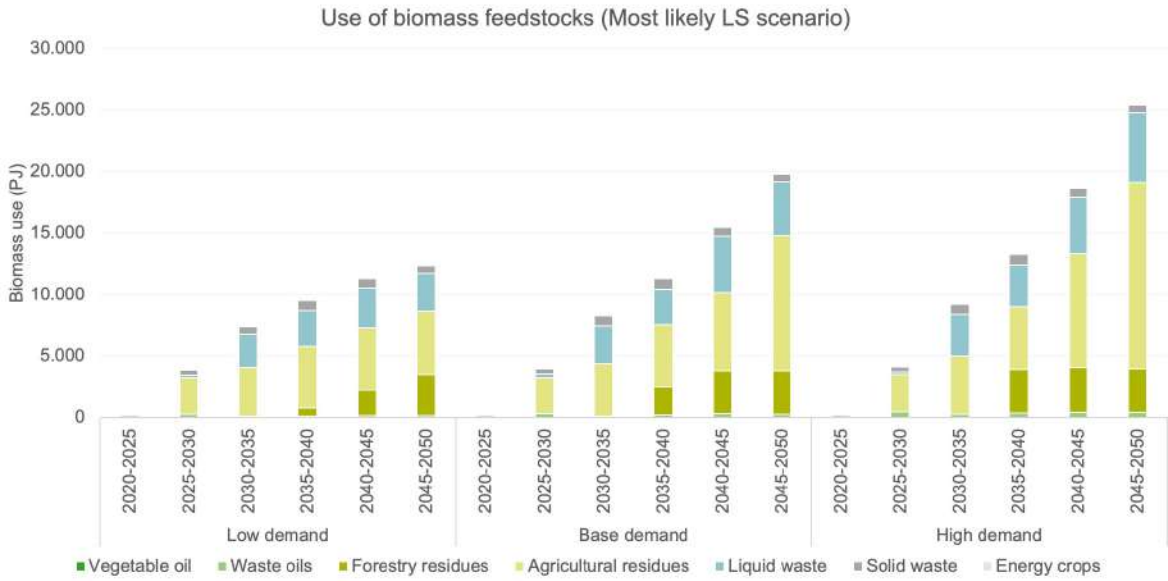

Figure 9.24: Biomass deployment in the ML LSBD scenario.

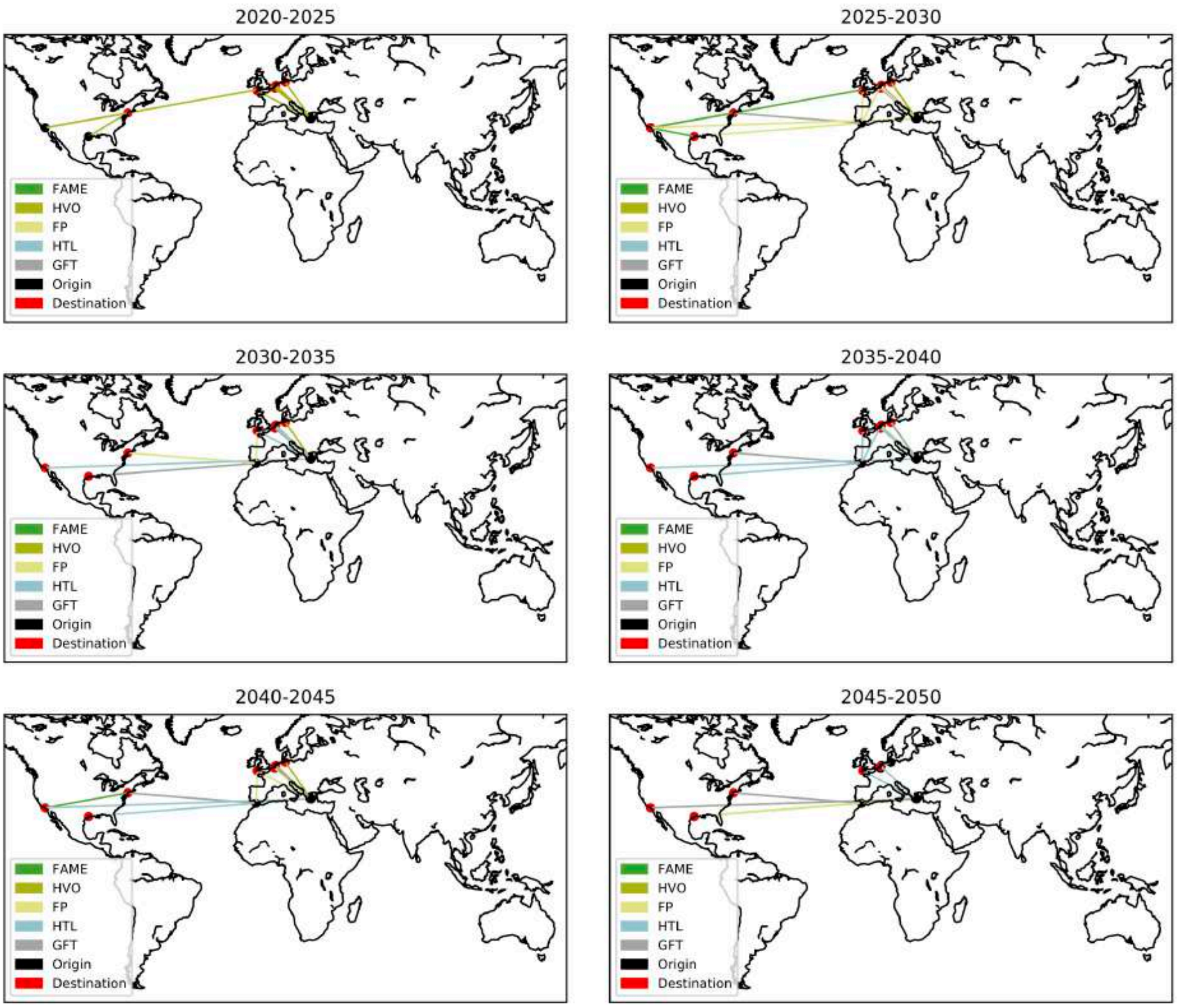

Figure 9.25: Biofuel trade flow in the ML LSBD scenario.

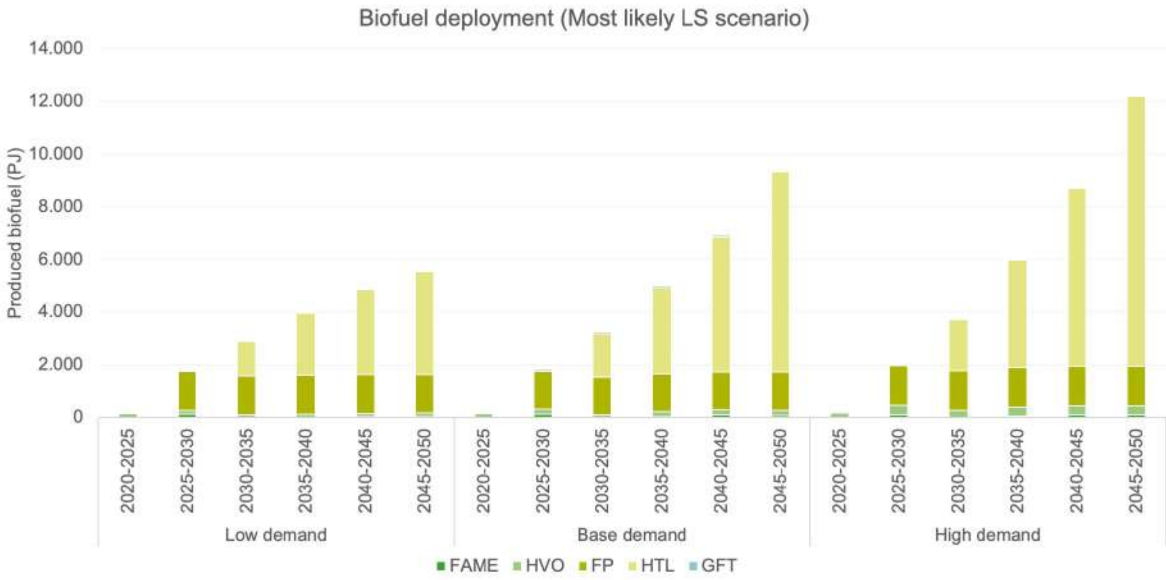

Figure 9.26: Biofuel deployment in the ML LSBD scenario.

Again, figure 9.22 shows that the preferred location for the setting up of new refineries is Southern Europe. In contrast to the Europe scenario, in this scenario also ports in Northern America have a demand for biofuels. It can be observed from figure 9.21, that this causes the need for HVO capacity in Vancouver at the start of the time period. This capacity is gradually increased with HTL upgrading facilities in Northern America. HTL refineries are added in Houston and Long Beach. In Europe, fast-pyrolysis also plays a significant role, but HTL is still the preferred technology.

The intermediate trade flows shown in figure 9.23, indicates significant trade in vegetable oils over the entire studied period. These oils are mainly imported from Asia. The eventual biomass mix in the ML LS scenario converges to a mix of forestry residues, agricultural residues, solid waste, and liquid waste. However, the use of agricultural residues prevails.

9.4. World

In this section, both the LS and HS World scenarios are studied. The biofuel demand in both scenarios are based on reaching the IMO targets, using only biofuel and Liquefied Natural Gas (LNG). In this scenario, the absolute shipping energy demand will experience a significant increase. The emission reduction targets of the IMO are set proportional to 2008 levels, which induces an extremely large required volume of renewable fuel to reach these targets. The structure of the studied scenarios in this section are depicted in figure **??**.

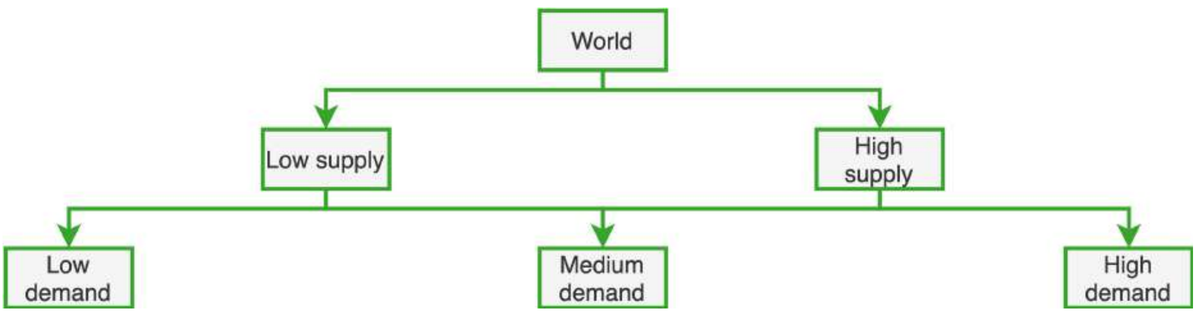

Figure 9.27: Structure of studied scenarios in this section.

9.4.1. World Low supply (LS) scenario

In this scenario, a conservative estimation of biomass availability is combined with a rapidly increasing global demand for biofuels. This demand is driven by a fictitious mandate for renewables fuels, implemented on a global level by the IMO.

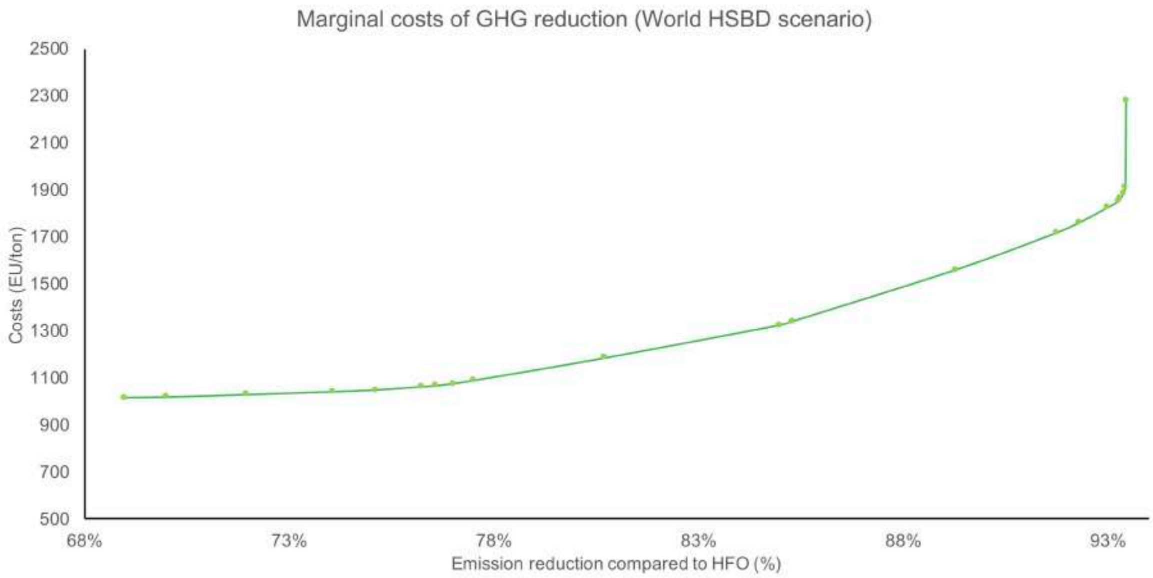

Figure 9.28: Marginal cost curve of World LSBD scenario.

The marginal costs curve for the World LS scenario is drawn in figure 9.28. The desired trade-off is found to be at an average fuel cost of 1087 EU/ton for a GHG reduction of 77.5 %. The results from the World Low Supply (LS) scenario are depicted in the following figures.

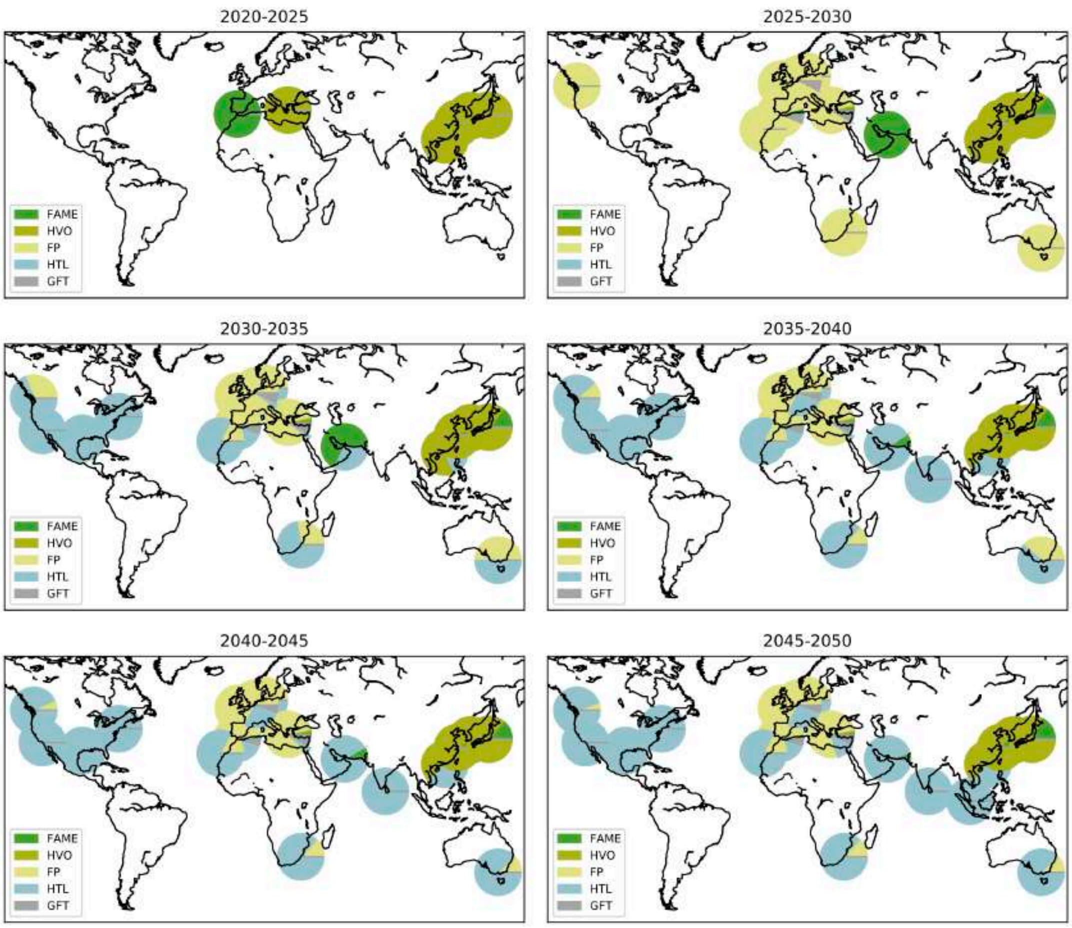

Figure 9.29: Refinery locations in World LSBD scenario.

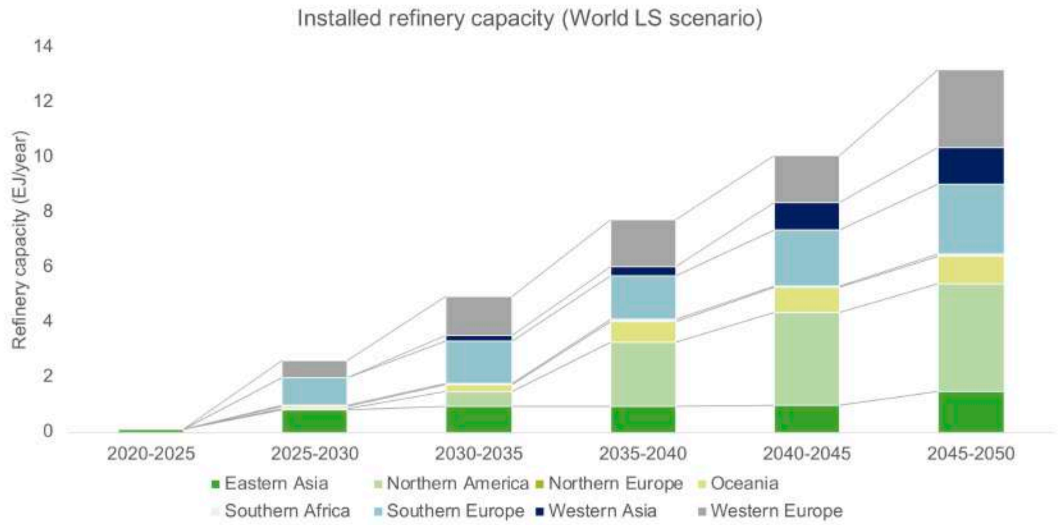

Figure 9.30: Refinery deployment in World LSBD scenario.

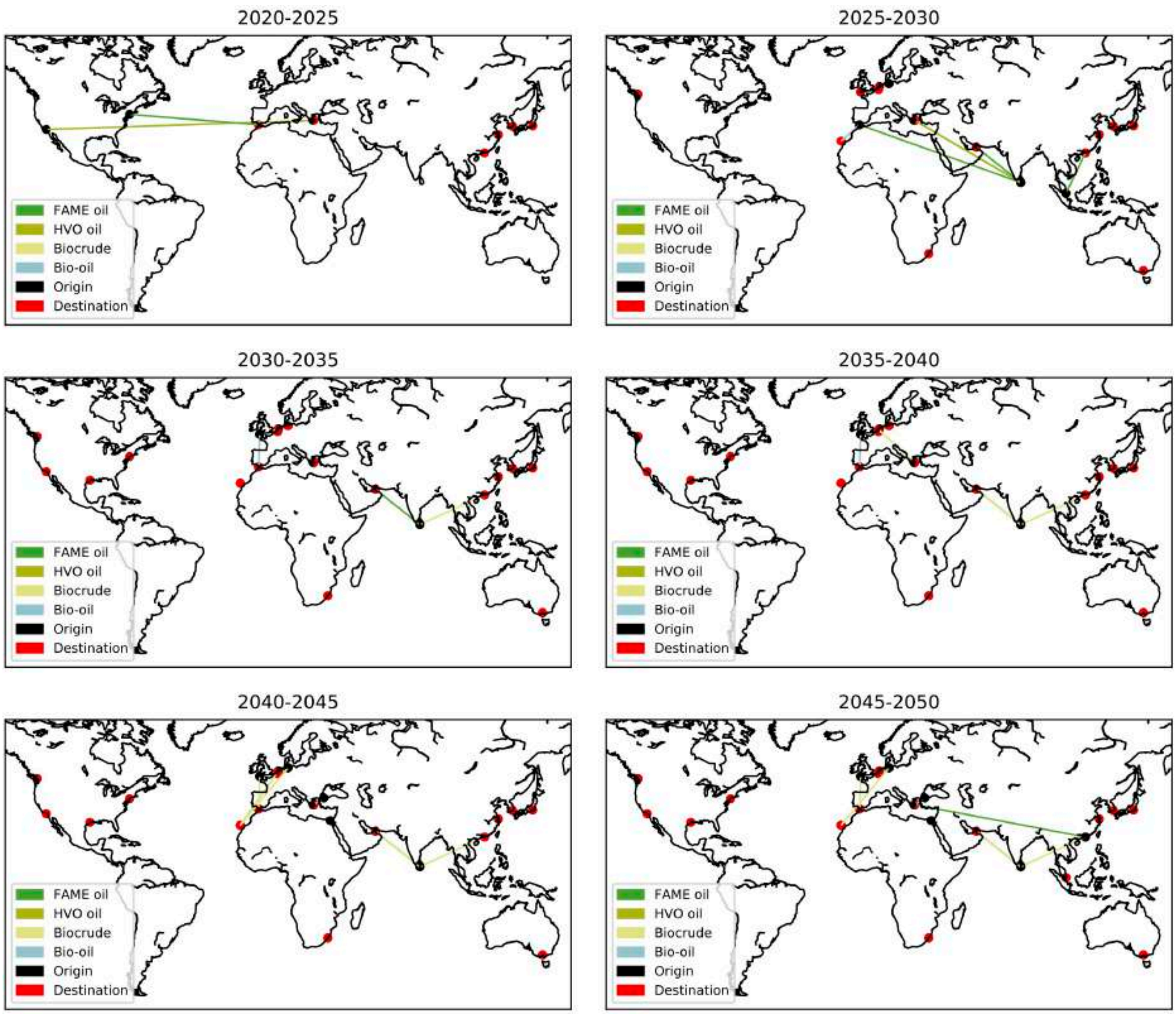

Figure 9.31: Flow of intermediate in World LSBD scenario.

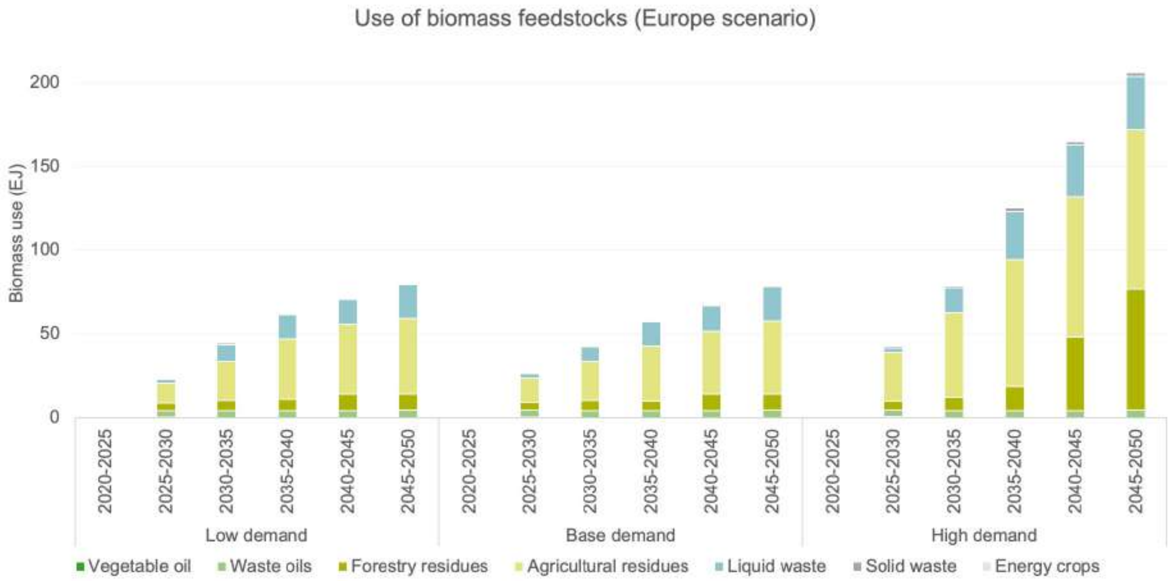

Figure 9.32: Used biomass types in World LSBD scenario.

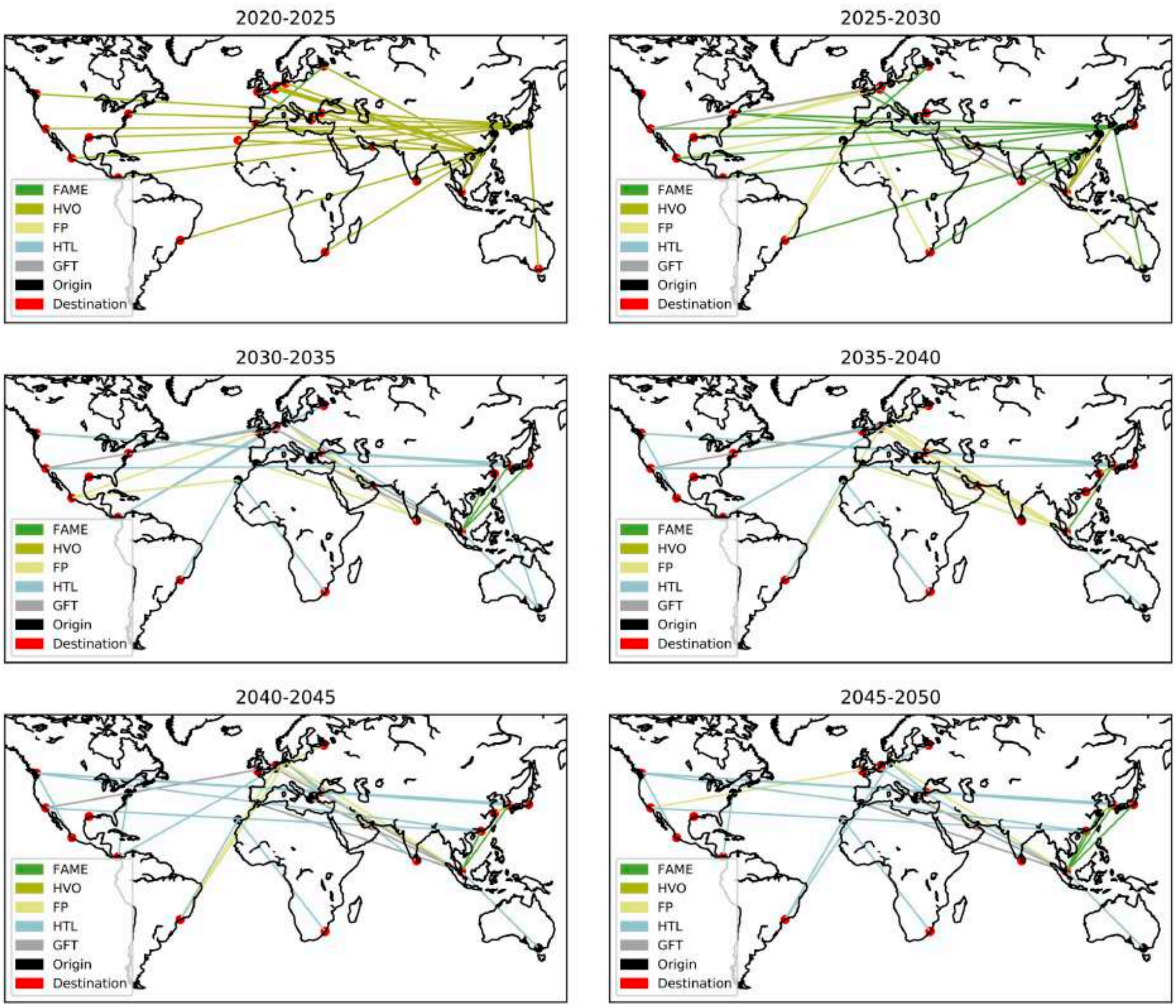

Figure 9.33: Flow of biofuel in World LSBD scenario.

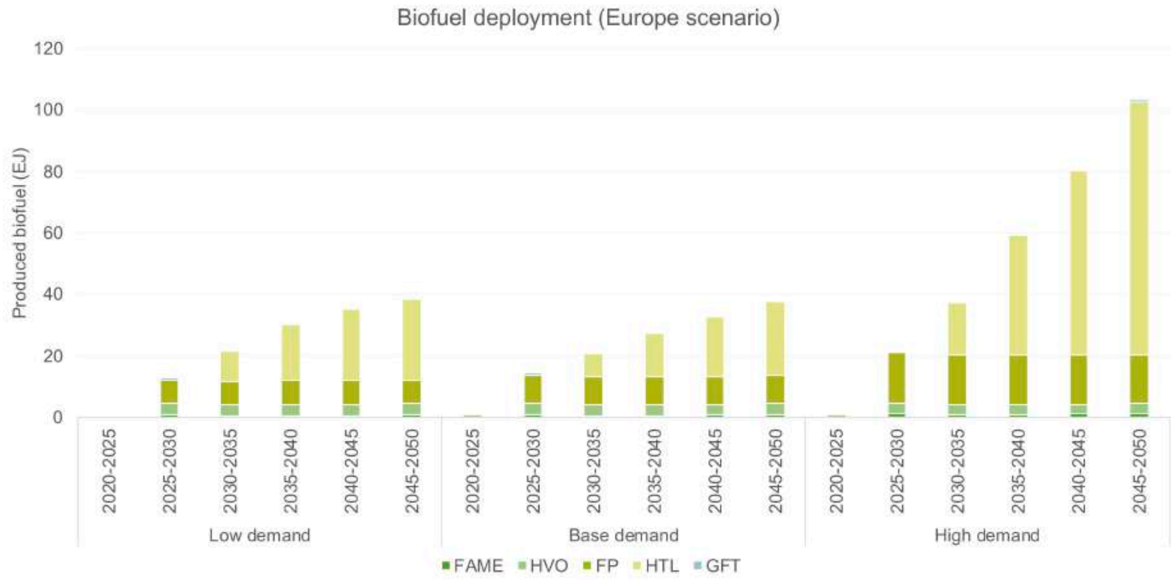

Figure 9.34: Used biofuel types in World LSBD scenario.

Figure 9.29 indicates the distribution of refinery locations over the studied period. Firstly, the model chooses to centralize FAME and HVO refineries in Southern Europe and Eastern Asia. In this first period, Southern Europe imports oils and fats for the production of these fuels. Eastern Asia uses domestic vegetable/waste oil supply. When Fast-Pyrolysis (FP) is introduced, additional refineries are constructed, especially in areas where there is a shortage of oily feedstocks. In the following time frames, Hydrothermal Liquefaction (HTL) starts to dominate biofuel production. It can be observed from figure 9.30, that there are in essence three refinery hot spots in this scenario, Western Europe, Southern Europe, and Northern America. However, also Eastern Asia and Oceania play a significant role. During the transition from the first period to the second period, a significant increase in biofuel production capacity is required to fulfill the demand. This originates from the correction on the admixture rate due to the limited vegetable/waste oil supply, which was discussed in section 9.1.

The resulting trade-flows in this scenario are fairly different from the other scenarios. The trade flows of the intermediate bio-energy carriers are shown in figure 9.31. It stands out that most regions use domestic biomass for the production of biofuel. Only during the first two time periods, the EU imports oily feedstocks from Northern America and Southern Asia. It is shown in figure 9.32 that mainly agricultural residues and liquid waste streams are used for the production of biofuel. For the High Demand (HD) scenario, forestry residues are increasingly used from 2035 on-wards.

In contrast to the Europe and Most-likely scenario, the World scenario induces significantly more trade of the end-product, which is shown in figure 9.33. This is caused by the fact that refineries are available in most regions/port (see figure 9.35) and thus fuel production is mostly done domestically. Energy imbalances are corrected by the trading of the biofuel itself in between regions. This seems to be a logical trend, seeing that biofuels are more energy-dense compared to the intermediate products. The preferred use of conversion technologies is shown in figure 9.34 and is comparable to the other studied scenarios.

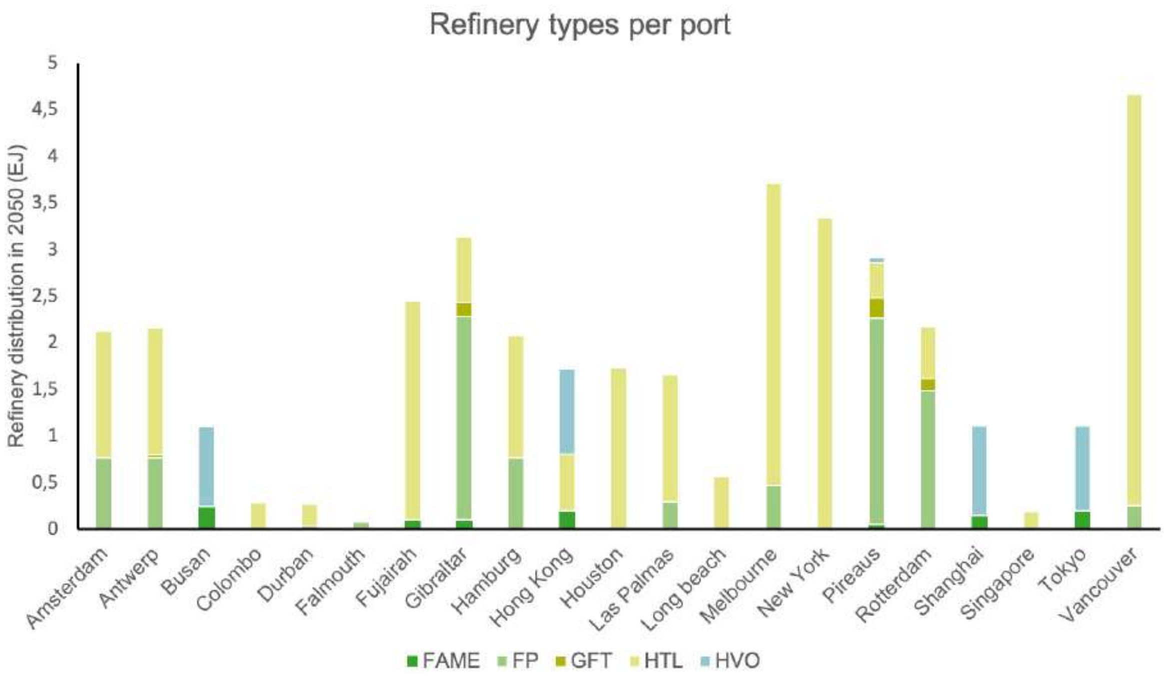

Figure 9.35: Refinery types per port in World LSBD scenario.

9.4.2. World High Supply (HS) scenario

In the World High Supply (HS) scenario, a large amount of biomass is assumed to be available for the production of marine biofuels. Compared to the World Low Supply (LS) scenario, the admixture rate in the first period is set to a higher value, which was already discussed in section 9.1. The marginal cost curve is drawn in figure 9.36. The most feasible trade-off is found to be at 79 % GHG reduction compared to HFO at a cost of 1081 Eu/ton. The average fuel cost to achieve such emission savings is thus significantly more expensive than the previously studied scenarios. The main reason for this is that the enormous demand causes the need for the use of feedstocks that are more difficult to access. Additionally, the desired volumes induce the need for transport of both the intermediate bio-energy carrier and the biofuel. Using the associated weight factors, the World HS scenario is simulated.

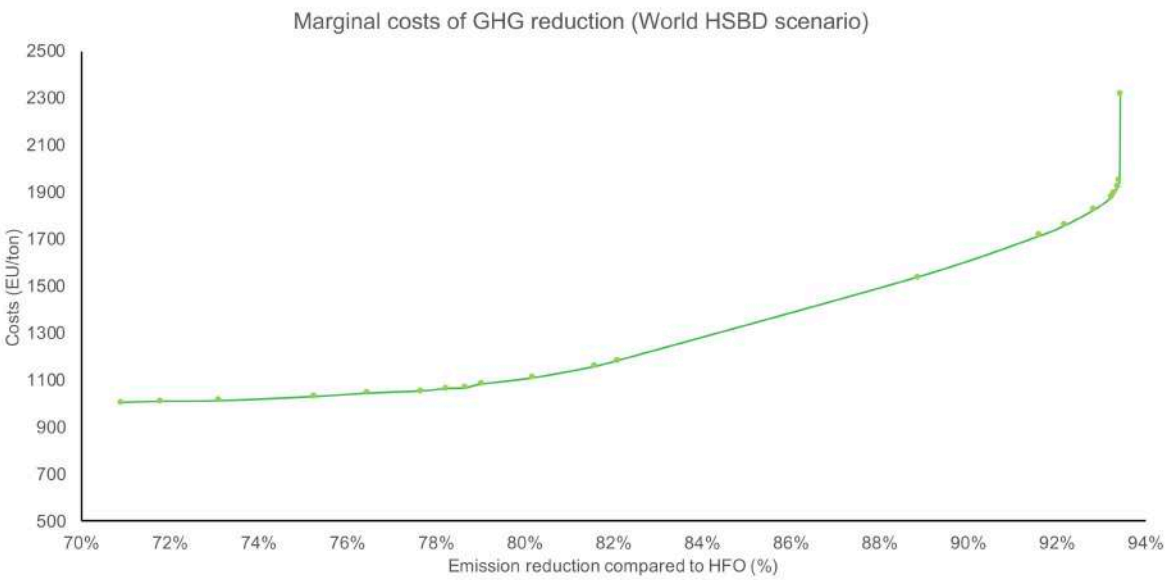

Figure 9.36: Marginal cost curve for World HSBD scenario.

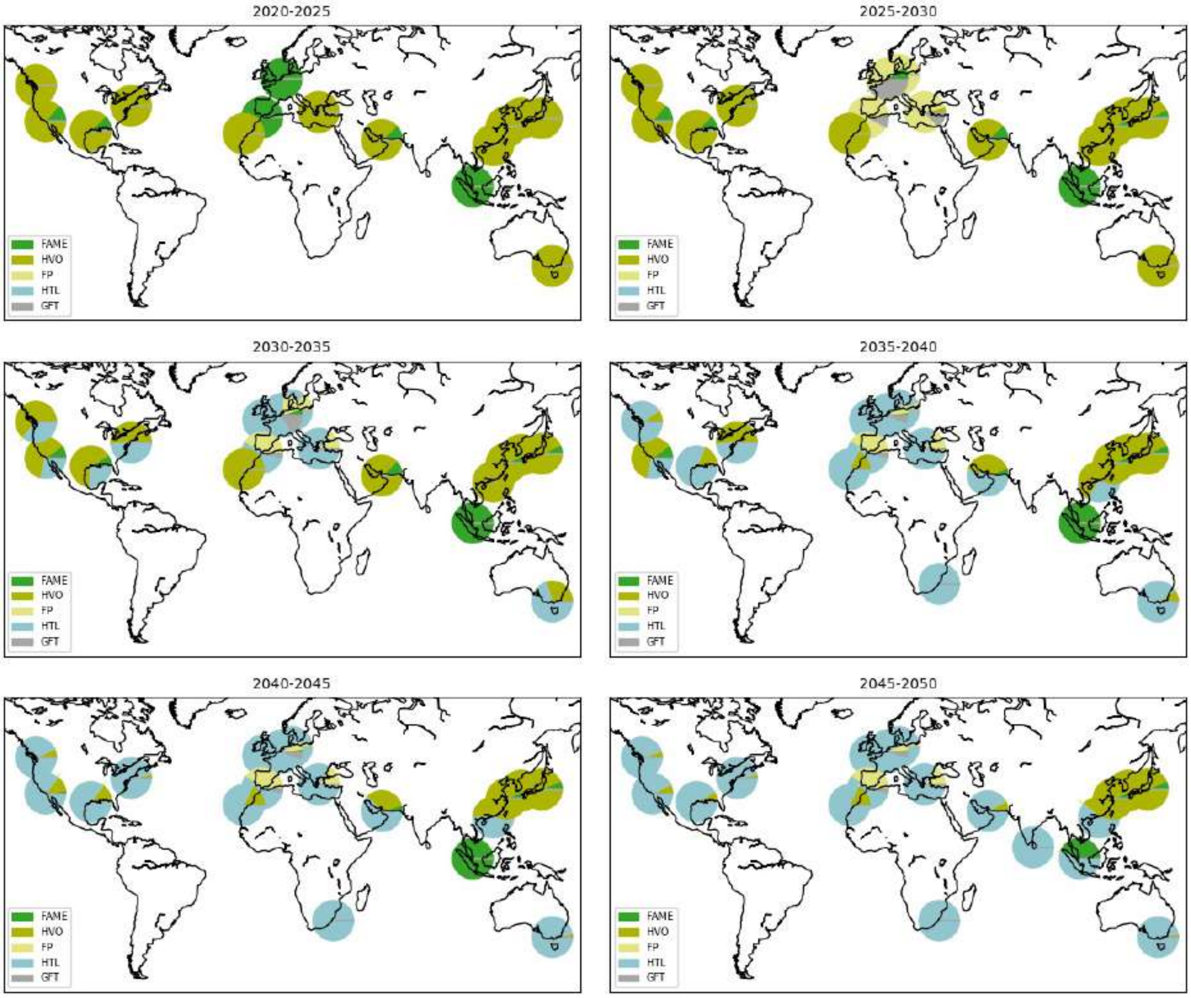

Figure 9.37: Optimal refinery locations for World HSBD scenario.

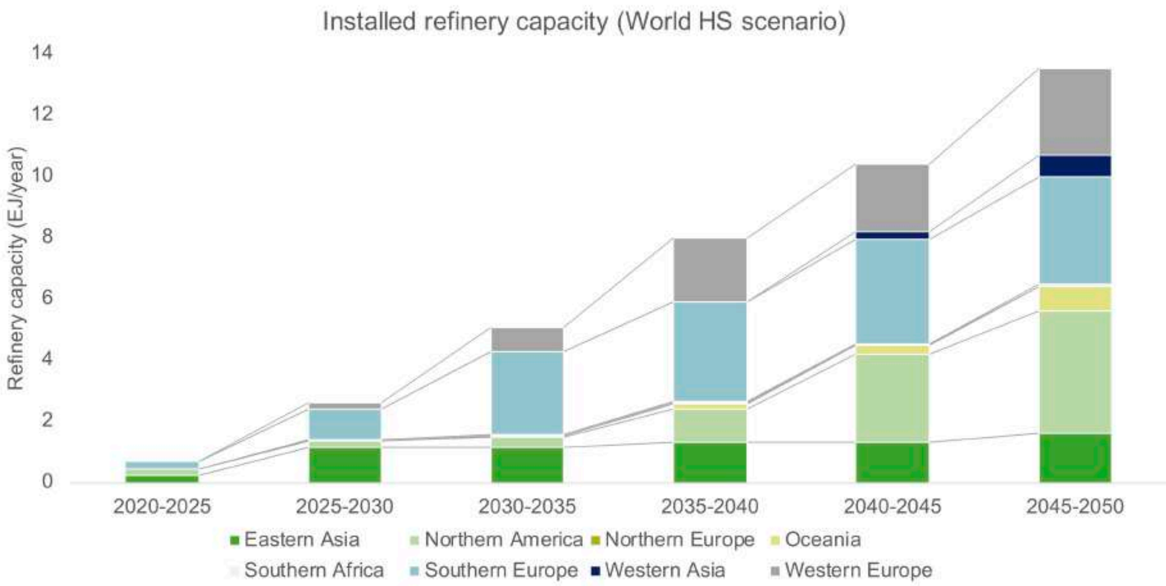

Figure 9.38: Optimal refinery deployment for World HSBD scenario.

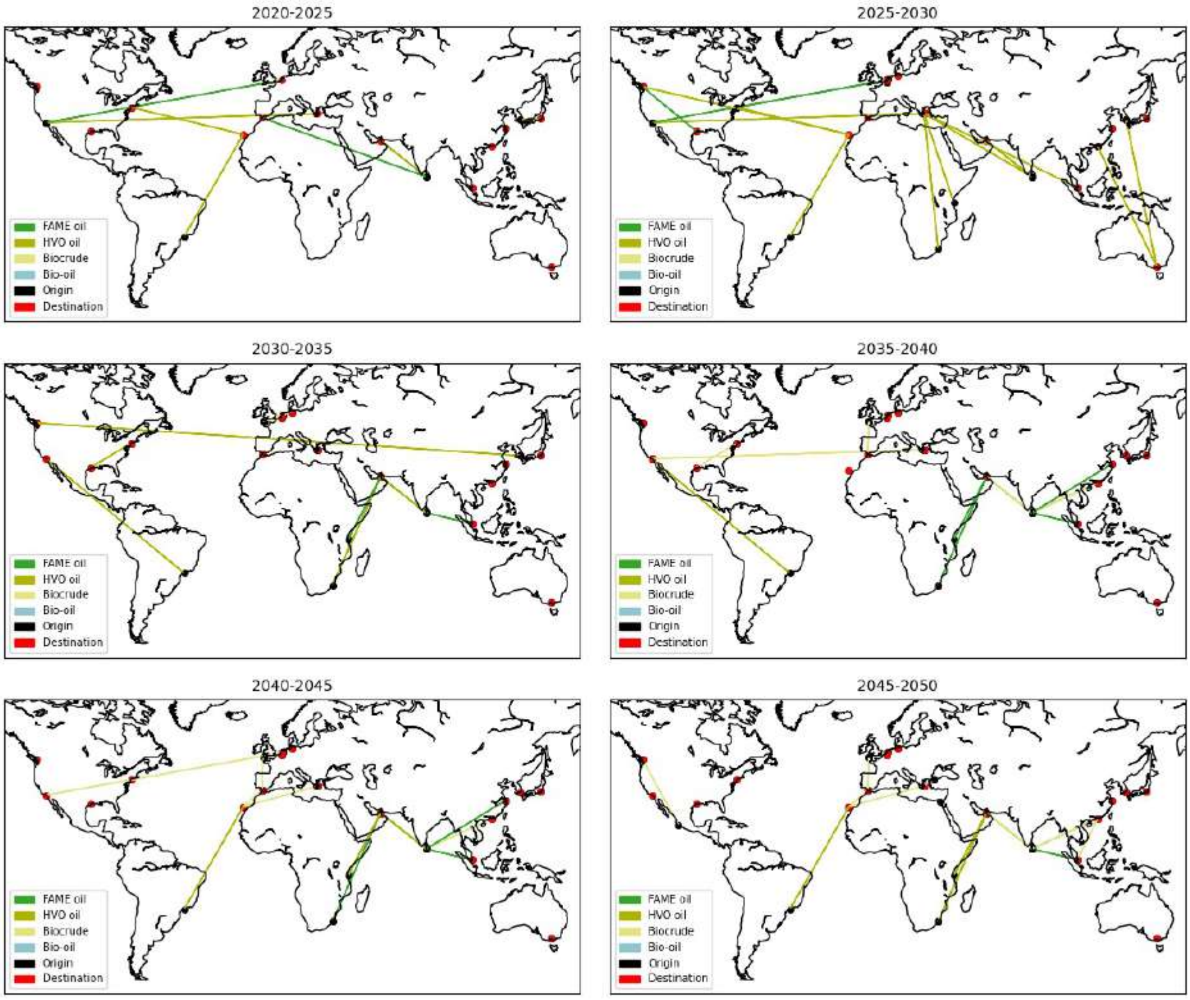

Figure 9.39: Intermediate trade flow in the World HSBD scenario.

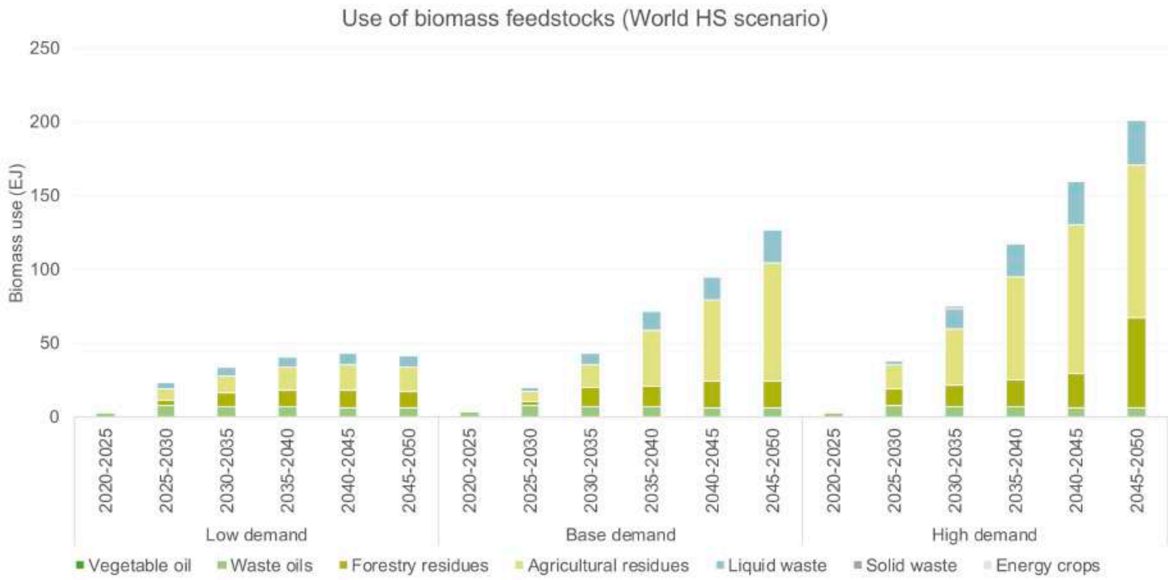

Figure 9.40: Biomass deployment in the ML LSBD scenario.

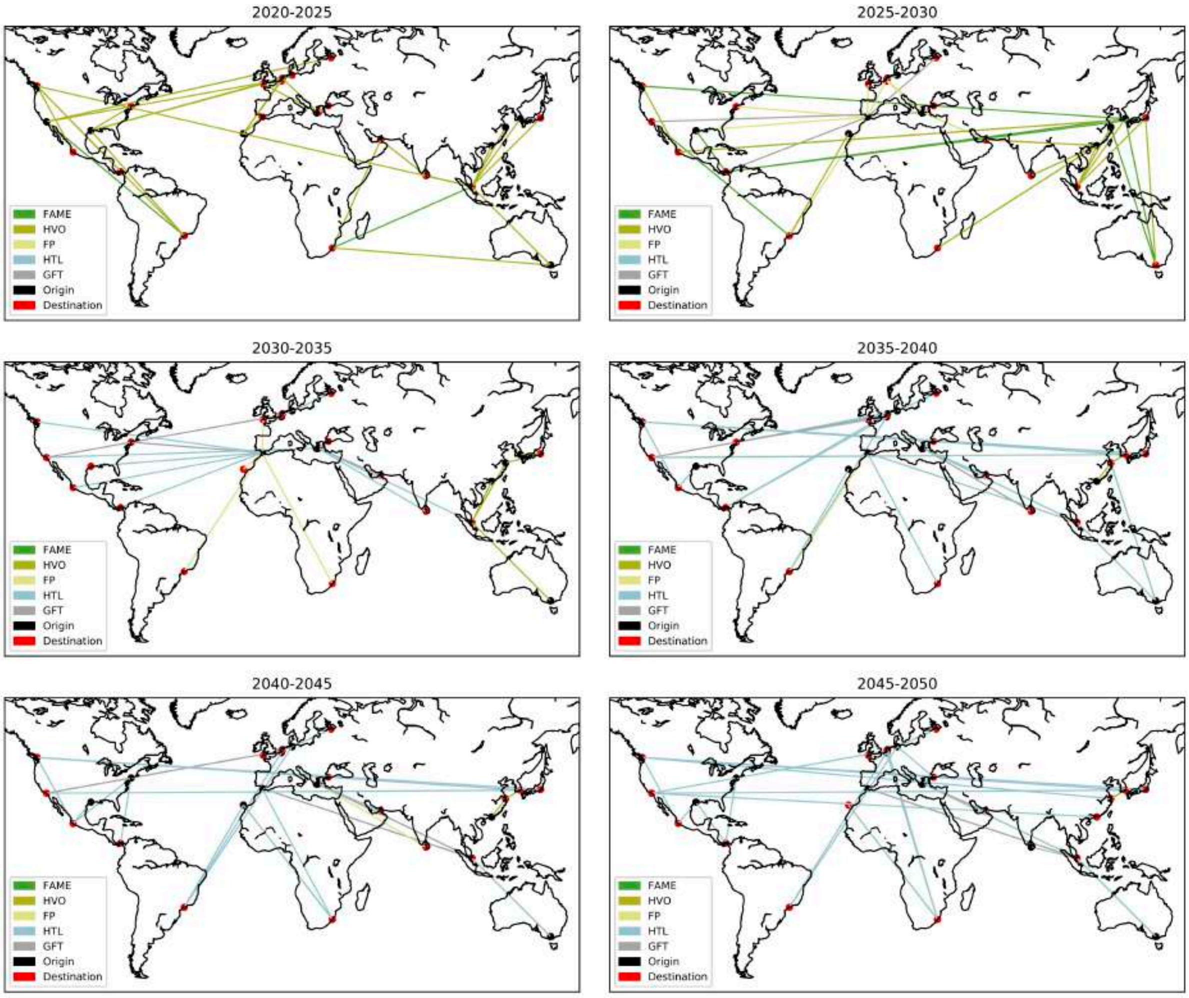

Figure 9.41: Biofuel trade flow in the World HSBD scenario.

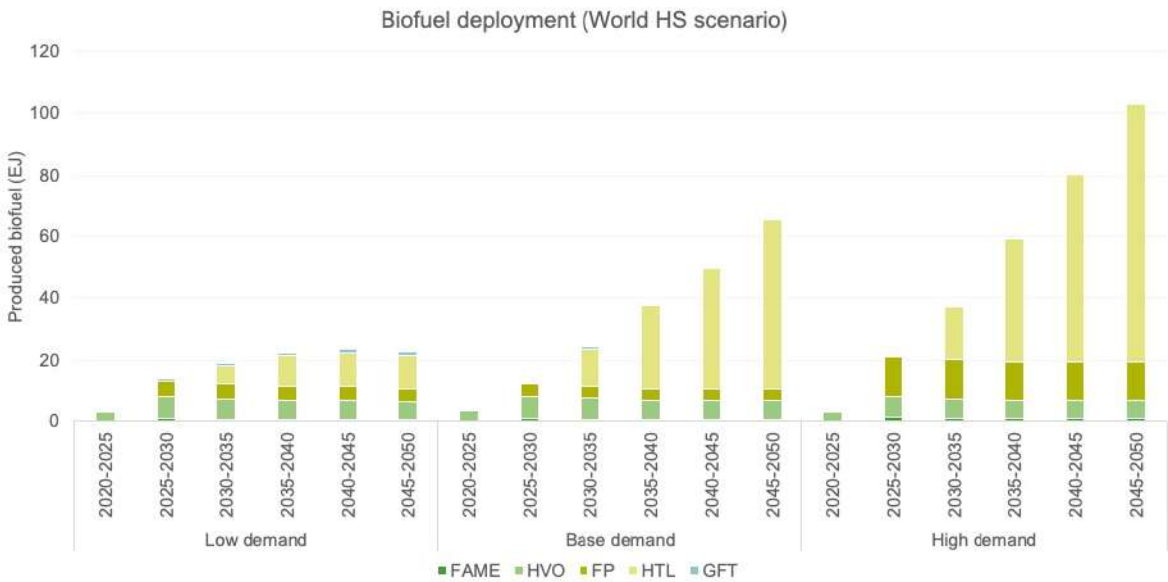

Figure 9.42: Biofuel deployment in the World HSBD scenario.

From figure 9.37 it becomes evident that FAME and HVO capacity is distributed over most of the regions. This is a significant difference compared to the World Low Supply (LS) scenario, in which FAME and HVO capacity was added only in Asia and Europe. The reason for this difference is the additional availability of oils and fats in other regions. This also leads to a more modest transition to advanced conversion technologies as compared to the World LS scenario. Therefore, it can be stated that regional availability of oils and fats has a major influence on refinery location decision making. Figure 9.38 shows that initially, Eastern Asia is the preferred refinery hub. Over time, Western Europe, Southern Europe and Northern America are gradually increasing their refinery capacity.

The trade-flows shown in figures 9.39 and 9.41 show a higher mobilization rate of oils and fats as compared to the World LS scenario. Also, the model prefers the use of waste oils over vegetable oils, which is shown in the biomass distribution graph in figure 9.40. Comparable to the previous scenarios, the choice of biofuel production technologies shows a tendency to the use of HTL, which is depicted in figure 9.42.

Figure 9.43 indicates the most feasible distribution of conversion technologies for each port by 2050. This indicates that HTL is eventually located in each port, while HVO production facilities should be situated in Eastern Asia.

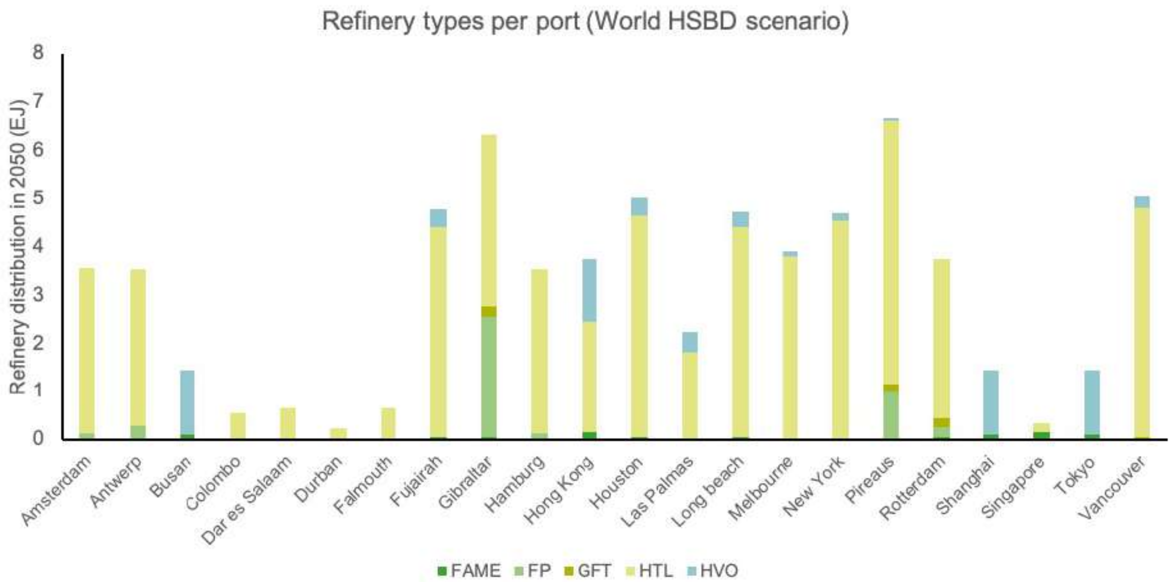

Figure 9.43: Refinery types per port in World HSBD scenario.

9.5. Comparison of scenarios

In this section, the previously discussed scenario results are compared to each other. While doing so, the influence of the embedded uncertainty in the supply and demand scenarios can be determined. Firstly, the cost performance of biofuels for each scenario is compared. Secondly, the consistency of the used feedstocks and biofuel production technologies are compared. Lastly, the main importing and exporting regions of both the intermediate bio-energy carrier and the biofuel are compared for all scenarios.

9.5.1. Comparison of costs and emissions

In figure 9.44, the marginal cost curves of all scenarios are plotted. All marginal cost curves show approximately the same trend. However, it is visualized that the different geographical demand scenarios cluster together. Hence, the spatial distribution of biofuel demand influences the marginal costs of GHG emissions.

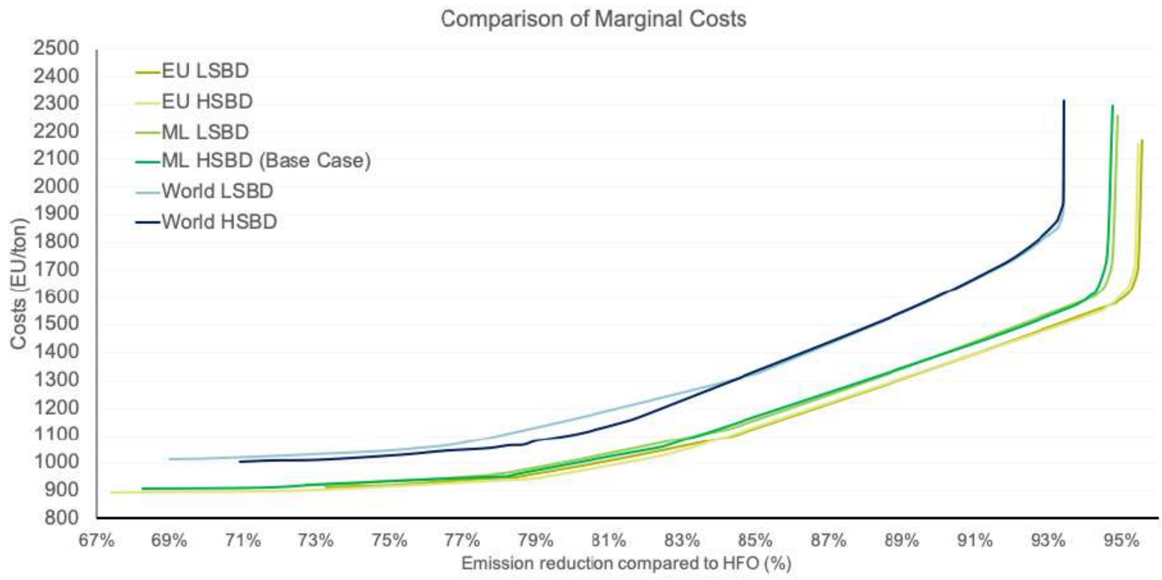

Figure 9.44: Comparison of marginal costs for all studied scenarios.

It can be seen from figure 9.44 that a higher demand for biofuels results in a higher cost for GHG reduction. The reason for this is the fact that increased demand leads to the usage of biomass that is more polluting because it is harder to access and thus requires more transport efforts. Additionally, this leads to the use of more expensive feedstocks with higher associated costs.

When comparing the average fuel costs over time for different scenarios, the same trend is discovered. In figure 9.45, the average fuel costs are plotted out against the studied periods.

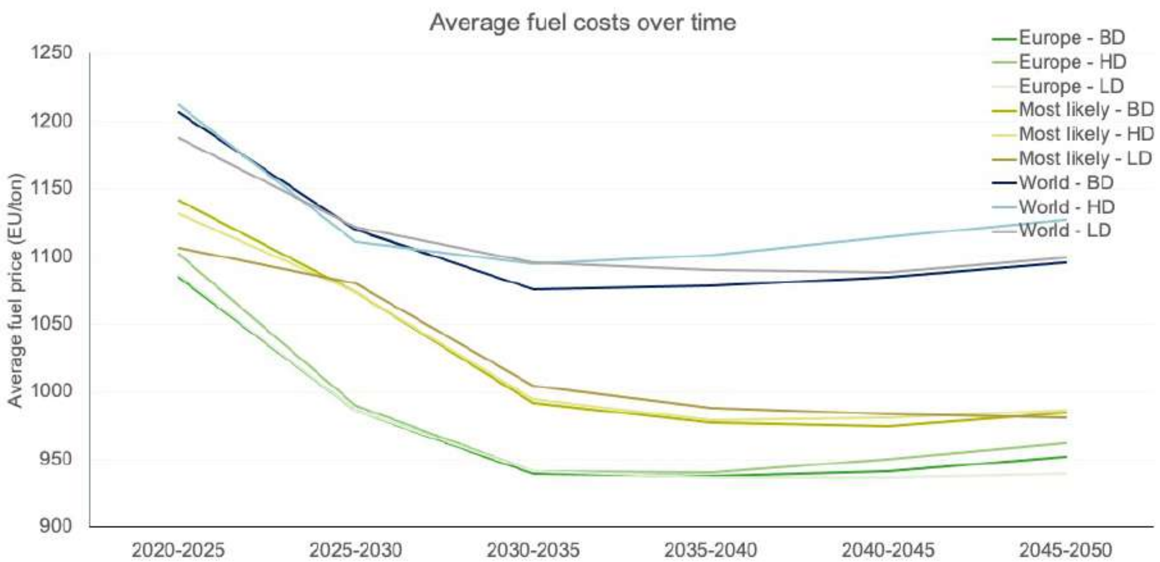

Figure 9.45: Comparison of average fuel costs for all studied scenarios.

It should be noticed that at first, the average fuel costs decrease. This is caused by the setting up of larger facilities, inducing economies of scale. Additionally, the introduction of advanced biofuel production technologies like Fast-Pyrolysis (FP), Hydrothermal Liquefaction (HTL), and Gasification Fischer-Tropsch (GFT) pave the way for the use of cheaper feedstocks. However, after a certain period, the average fuel costs experience a slight increase. This is again a result of the need for biomass that is more difficult to access, which drives up the feedstock costs.

In figures 9.46 and 9.47 a comparison of cost and emission distribution for the studied scenarios is shown.

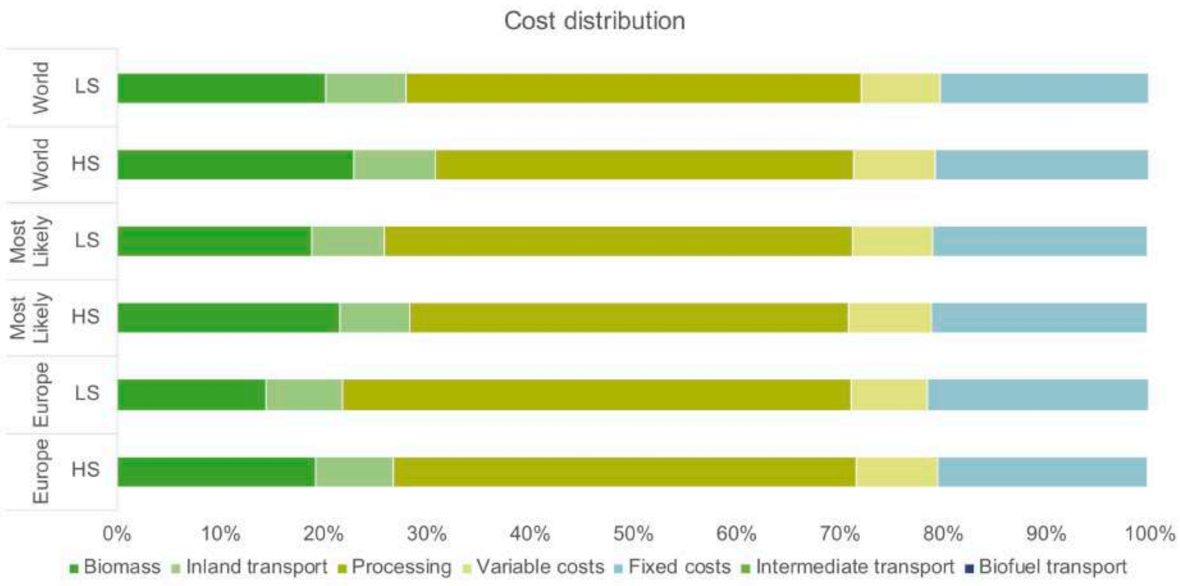

Figure 9.46: Comparison of cost contributions for all studied scenarios.

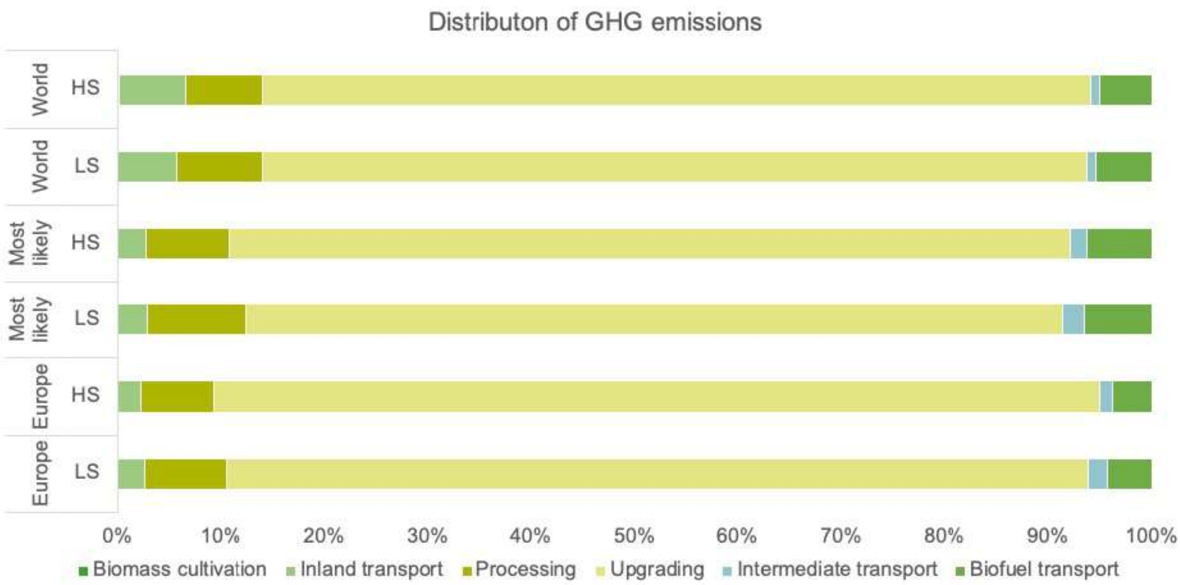

Figure 9.47: Comparison of GHG emissions contributions for all studied scenarios.

The distribution of costs and emissions are comparable for all studied scenarios. Around 70% of the costs can be assigned to the production of the intermediate bio-energy carrier. However, production of the intermediate bio-energy carrier does only account for around 10% of GHG emissions. Upgrading of the intermediate product accounts for 80-85 % of total GHG emissions and the sum of all transport accounts for the remaining 10%.

9.5.2. Comparison of feedstock use and biofuel deployment

Besides the influence on the economic performance of the supply and demand scenarios, it would also be interesting to see whether these uncertainties have an effect on the choice for a certain feedstock or conversion technology. Figure 9.49 compares the usage of biomass feedstocks for the different supply and demand scenario combinations.

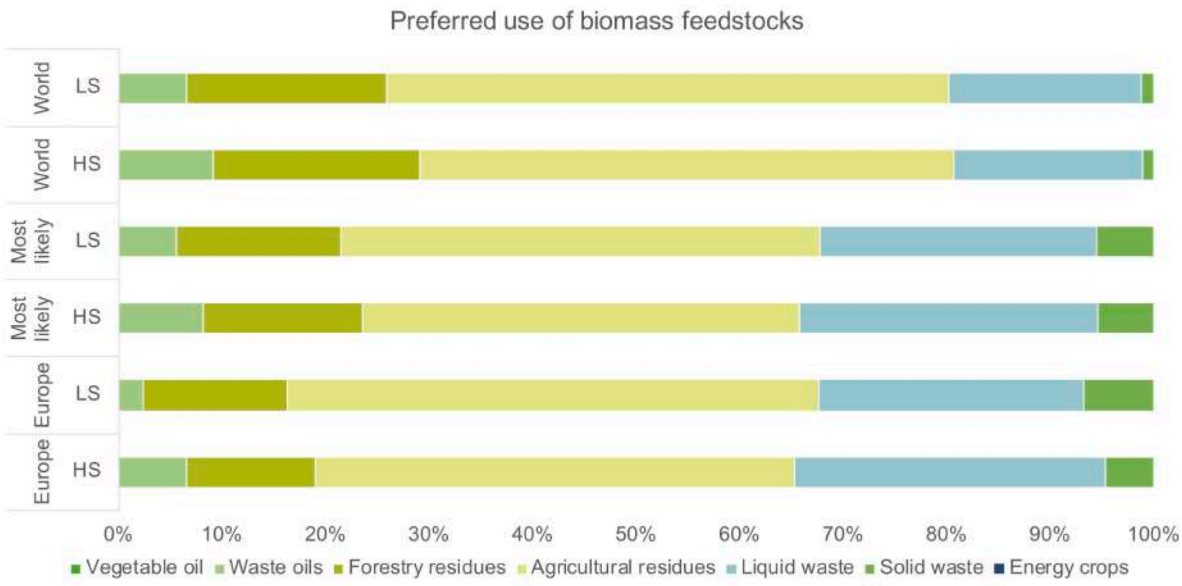

Figure 9.48: Comparison of used biomass feedstocks for all studied scenarios.

It can be identified that the influence on biomass choice is minor. In the Low Supply scenarios, fewer waste oils are available. Furthermore, the relative use of solid waste is decreased in the World scenario. This is mainly caused by the higher availability of solid waste in urban areas, where there is a mature waste collection system. These areas especially include Northern America and Europe, which were mainly studied in the Europe and Most-Likely scenario. Agricultural residues is the feedstock category that is mostly used in all scenarios. This feedstock has high potential availability and is available in most studied regions.

In figure 9.49, the percentage usage of the different conversion technologies for all studied scenarios is shown.

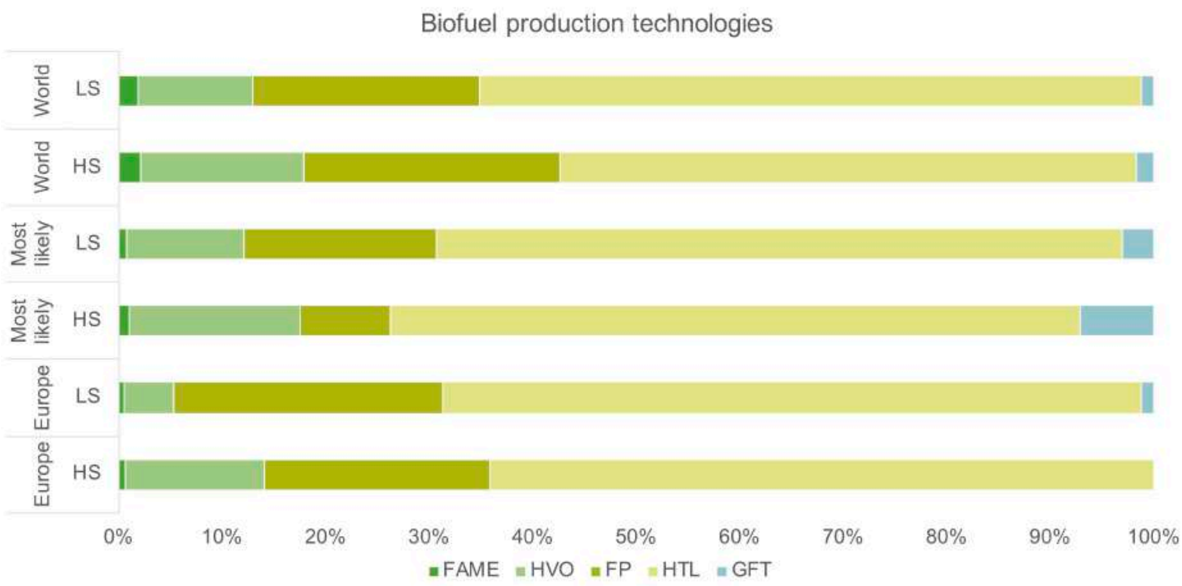

Figure 9.49: Comparison of used biofuel production technologies for all studied scenarios.

Like mentioned before, the preferred technology in all scenarios is HTL. The share of Fast-Pyrolysis is smaller, but this technology is also used since it is expected to be commercial earlier on. Generally, the model chooses HVO over FAME due to its stronger environmental performance.

9.5.3. Comparison of trade-flows

It was shown in the previous analysis that the different demand and supply scenarios have a significant influence on the most feasible locations of bio-refineries. Changing the spatial distribution of bio-refineries indistinctly induces a change in trade-flows. In figures 9.50 and 9.51, the major exporters and importers of the intermediate bio-energy carriers are displayed.

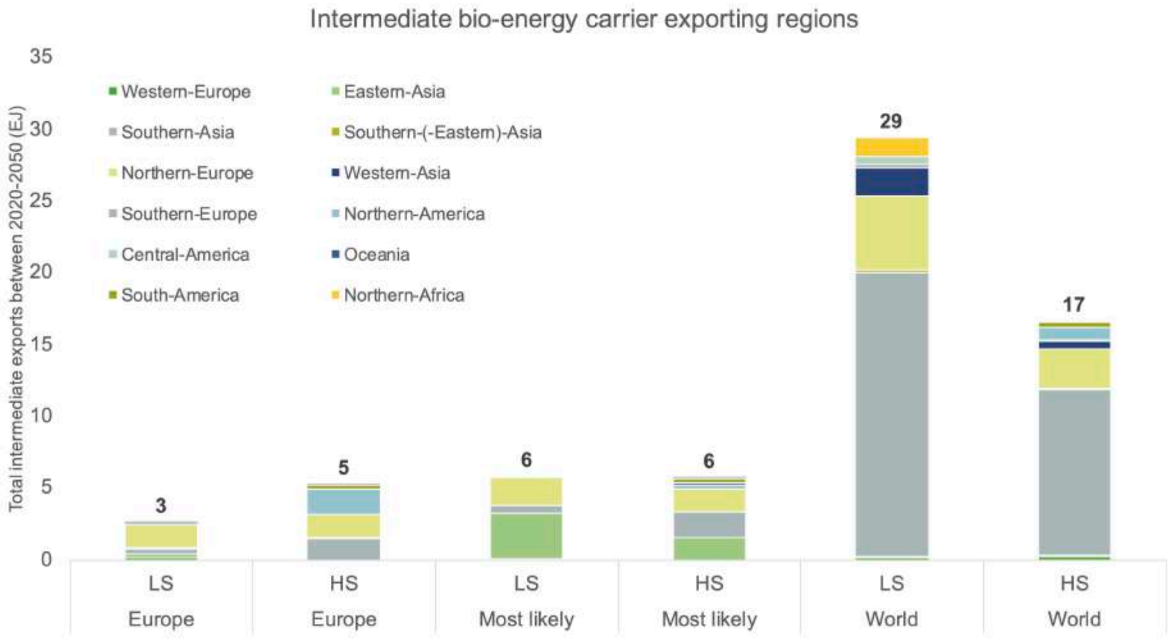

Figure 9.50: Main exporting regions of intermediate bio-energy carriers. The total exported amount between 2020-2050 is given in Peta Joule (PJ).

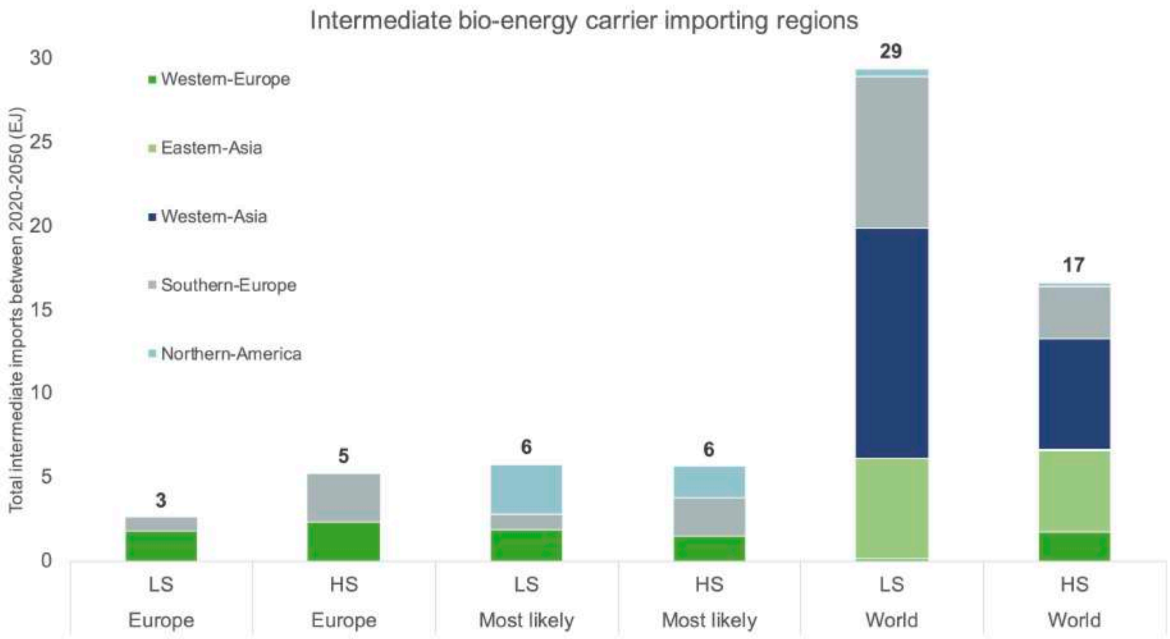

Figure 9.51: Main importers of intermediate bio-energy carriers. The total imported amount between 2020-2050 is given in Peta Joule (PJ).

The regions that export intermediate bio-energy carriers essentially supply biomass to other regions, seeing that only domestic biomass is used to produce the intermediate products. A shift in biomass supplying regions is observed when the spatial distribution of demand changes. In the European Low Supply (LS) scenario, the main exporters of biomass are Southern Asia, Eastern Asia, and Northern America. The main importing regions are Western Europe and Southern Europe, which is where the bio-refineries are located in the Europe LS scenario. In the Europe HS scenario, available biomass supply increases. This leads to an increase in the share of Northern American biomass exports. This is mainly due to the increased availability of oils and fats in that region. Also, the imports of intermediate products shift slightly to Western Europe.

In the ML LS scenario, Houston, Vancouver, New York, and Long Beach also gain demand for biofuels, which is expressed in a growing share of imports of the intermediate product to Northern America. This significantly increases the exports of the intermediate products from Eastern Asia. In the ML HS scenario, the increased availability of biomass leads to more refinery capacity in Western Europe. Northern America imports oils and fats from regions that are more in vicinity, like Central and South America.

In the World scenario, the distribution of imports and exports changes. It was already mentioned before that in the case of worldwide demand, less of the intermediate product is transported while biofuel transport is increased. In the LS scenario, Eastern Asia, Western Asia, and Southern Europe are the refinery hubs. Southern Asia is the main exporter of the intermediate bio-energy carriers, which is caused by the large availability of liquid waste in that region. When potential biomass supply increases, Southern Asia stays the main exporter of the intermediate bio-energy carrier. In the World scenario, increased biomass supply leads to a decrease in intermediate imports, seeing that more biomass can be sourced domestically.

Next to the intermediate trade-flows, optimal biofuel trade-flows could also change due to varying biomass supply availability and spatially changing demand. The main exporters and importers of biofuel are shown in figures 9.52 and 9.53.

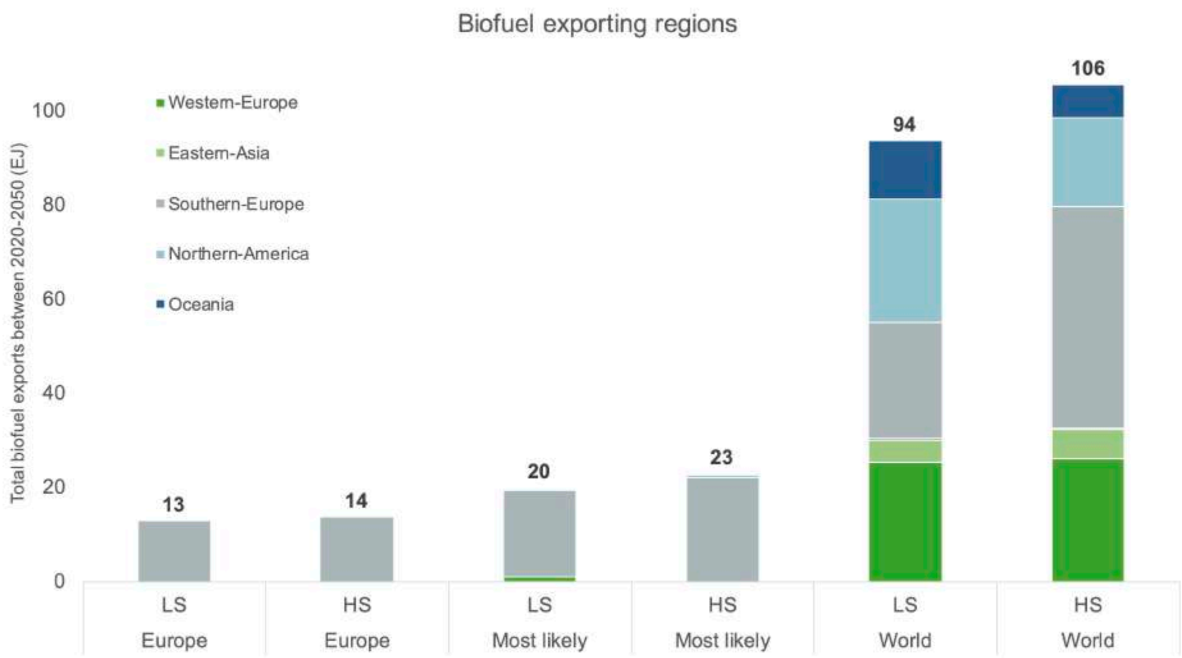

Figure 9.52: Main biofuel exporting regions. The total exported amount between 2020-2050 is given in Peta Joule (PJ).

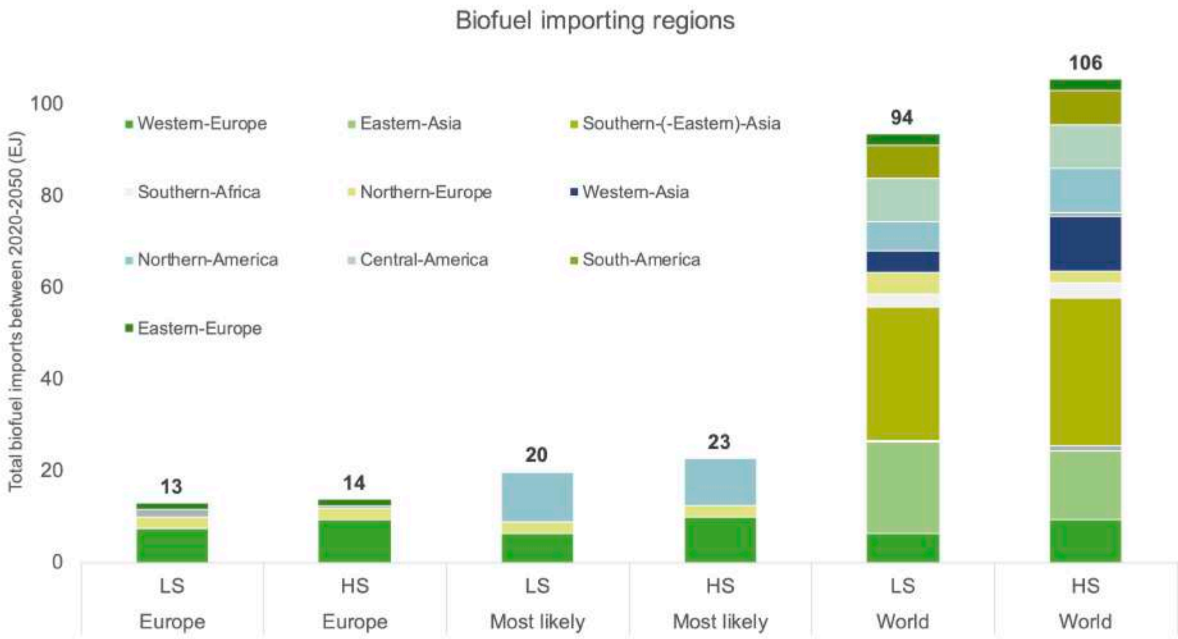

Figure 9.53: Main biofuel importing regions. The total imported amount between 2020-2050 is given in Peta Joule (PJ).

The main exporting regions of biofuel are relatively constant for the Europe and Most-Likely scenarios. Southern Europe is the main exporter of biofuels for these scenarios, both for the Low Supply (LS) and High Supply (HS) scenarios. In the European scenarios, Western Europe imports large volumes of biofuel from Southern Europe. In the Most-Likely (ML) scenario, Northern America also imports a large share of biofuel. This seems a logical consequence of the spatial distribution of biofuel demand.

The world scenario is more interesting, seeing that it was already noted that there is increasing mobilization of biofuel. Western Europe, Southern Europe, Eastern Asia, Northern America, and Oceania are the largest exporters of biofuel. The largest importing region is Southern-Eastern Asia. This is mainly caused by the large biofuel demand from the port of Singapore. Remarkably, it is chosen to import biofuel to Singapore, rather than to built bio-refineries there. Additionally, some other biofuels importing regions are Western Asia, Central America, Southern America, and Eastern Europe.

An important side-note is the exclusion of geopolitics in this analysis. Hence, trade relations and import/export tariffs are not included. Also, existing fossil refineries could be converted to bio-refineries, which could cause a preference for setting up bio-refineries in places where fossil refineries are already present. However, the key takeaway from the resulting trade-flows is that it would be beneficial to make use of large centralized refinery hubs. Additionally, biomass should be sourced domestically as much as possible.

10
Discussion

The intention of this chapter is to reflect on this research and the obtained results. Some limitations on the research approach, optimization model, and model assumptions are discussed. Also, the additional value of this research, both from a societal and scientific point of view, is elaborated upon.

10.1. Reflection on the research approach

The goal of this research was to determine the potential of drop-in biofuels for the maritime industry. In the problem statement, several potential barriers to the use of drop-in biofuels were discussed. It became evident that there was uncertainty about the potential available supply of biomass that could be used for the production of marine drop-in biofuels. Additionally, the imbalance between the supply of biomass and demand for marine biofuels, taking into account the contribution of competing users, had not yet been properly mapped. Therefore, it was unknown what would be the optimal locations for the setting up of new biofuel refineries and which regions would be potential importers and exporters of intermediate bio-energy carriers and biofuels. It was also addressed that both costs and emissions play an important role in the potential of drop-in biofuels for the maritime industry. Hence, it was attempted to discover how these are structured and visualize the trade-off between them.

To provide answers to the sketched uncertainties, it was chosen to perform a strategical multi-objective optimization of the marine biofuel supply chain. This strategic supply chain optimization offers the opportunity to align the supply and demand for biomass feedstocks and biofuel. It was also recognized that the maritime sector operates internationally and should therefore be modeled on a global level. After a thorough literature review, it was decided to perform the strategic supply chain optimization using a Mixed Integer Linear Programming (MILP) model. For linear optimization, a simplex solver was used (Gurobi). Making use of this modeling technique provided rapid solutions.

Linear optimization was found to be a suitable approach for modeling the marine biofuel supply chain. However, during the modeling process, it also became evident that there are several non-linear relationships embedded in this problem. These non-linear relations were in this case modeled using piecewise discrete linearization. Although this approach was satisfactory for this purpose, non-linear optimization might enable more comprehensive modeling of relationships between costs, supply, and demand.

Within the MILP model, four sub-models were identified. The first sub-model is the determination of the available biomass supply. The second sub-model was described as the estimation of marine biofuel demand over time. The third and fourth sub-model are the refinery facilities and the transportation of commodities respectively. Due to the magnitude of the problem, it was decided to use static and data/literature driven approximations for these sub-models. In reality, fluctuating fuel prices would influence the spatial distribution of demand and regional scarcity of supply would drive up the local fuel price. Also, besides economies of scale, no cost reductions due to increasing technology efficiencies were taken into account. For the supply scenarios, imports and exports of most biomass categories were not pre-processed. This led to an overestimation of biomass availability in some areas. This overestimation was caused by the assignment of zero supply to regions in which supply was negative after deducting domestic demand. To prevent this, accurate import and export data was required, which was not available.

To capture the relative uncertainty that is embedded in the various sub-models, in total 18 scenarios were successfully executed. In this assessment, the presence of existing trade relations and import/export tariffs were not taken into account. In reality, these might be crucial for the emergence of biomass trade-flows. The following section will contain a comprehensive reflection on the outcomes that resulted from the mentioned scenarios.

10.2. Reflection on the model assumptions

Although the pre-intended solutions were extracted, the model and associated data collection contain some areas of improvement. The magnitude of the problem that has been attempted to be modeled is significant. Taking into account that it is difficult or even impossible to capture the full complexity of a system in a model, several assumptions are made. These assumptions are both present in the modeling approach and the gathering of model input and parameters. An overview of the assumptions is provided in table 10.1.

Table 10.1: Main assumptions and their expected consequences.

Assumption	Consequence
Static relationship between demand and supply	A different distribution of demand might have an influence on chosen locations for new bio-refineries and associated trade-flows.
Static cost and emission factors for transports	From the sensitivity analysis it was observed that possible deviations in system emissions are in the range of -6%/+3%.
Technological learning effects are not included	According to de Jong et al. [43] technological learning could decrease production costs by 10% over a 10 year period
Demand is based on compliance with RED II and IMO targets	The demand for maritime biofuels in this thesis is rather based on compliance with targets than on actual policies, seeing that such policies are non-existent at this stage. Therefore, the results from this study give an idea about required efforts to comply with GHG reduction targets using drop-in biofuels in shipping.
Exclusion of current trade flows (except for vegetable oils)	This results in a maximum overestimation of feed-stock availability of ± 8%.
Excluding detailed modeling of inland transport and routing optimization	Including route optimization might cause changes in optimal trade flows. For Eastern Europe, including Russia, this was expected to have an influence. The current solutions include no export of biomass from Eastern Europe. In the Asian bordering region, enough domestic biomass is available without imports from Russia. Hence, this assumption is not expected to greatly influence the results.
Geopolitical relationships are not considered	Existing trade relationships between regions were not considered in the optimization model to find. This might alter the resulting trade-flows and refinery locations.

The first important assumption is the static relationship between supply, demand, and fuel price. This topic was earlier touched upon but is an important assumption seeing that this greatly influences the location of supply and demand. This assumption was made based on the current implementation of the marine fuel infrastructure. According to Raucci [116], current marine fuel hubs stay relatively constant due to the strategic locations of ports like Singapore, Rotterdam, and Fujairah. It is therefore assumed that the demand for biofuel will follow the same trend as petroleum based marine fuels. Additionally, it is assumed that future regulations regarding mandatory blending prescriptions will be set-up in a way that prevents carbon leakage.

The second assumption is made during the modeling of transport. Static emission and cost factors are used related to inland and sea transport. This might under or overestimate the emissions/costs related to transporting. However, this assumption was addressed in the sensitivity analysis and was found to have a maximum impact of -6%/+3% on eventual emissions that are allocated to the fuel.

The third assumption is related to increasing efficiency gains within bio-refineries. New technologies often experience a learning curve in which efficiency gains lead to lower fuel costs. How this learning curve develops is highly dependent on R&D efforts [43]. Nevertheless, this learning effect is not explicitly modeled.

The demand and possible mobilization of biofuels are greatly dependent on the political context. This includes both new regulatory frameworks that include the use of renewable fuels and the existence of import and export trade-tariffs. In this study, demand is based on the RED II and IMO targets, but neither of them contains regulations regarding GHG emission reduction or prescriptive blending requirements of renewable fuels for shipping. Hence, the goal of this study was rather to show the efforts required to reach these targets as if shipping were included in these regulatory schemes.

Additionally, it was assumed that each considered region had a discrete amount of ports that served as nodes in the studied network. Therefore, detailed inland transport modeling and routing optimization was not included. As earlier stated in the scope of the research, for Eastern Europe this could influence the eventual development of trade-flows. However, in the current solutions no biomass from Eastern Europe was exported to other regions. Additionally, the regions bordering Russia were all found to have enough domestic biomass available.

Lastly, geopolitics and trade relationships between regions could influence the deployment of biomass trade flows and optimal bio-refinery locations. However, it was found to be difficult to address the concrete impact this might have on the results of this study.

Overall, the assumptions that were made seem to be valid and lead to limited impact on the results and associated conclusions.

10.3. Reflection on the model findings

Let us, first of all, look into the initially intended model outcomes to see whether they match with the actual outcomes. The model outcomes stated in figure 3.4 were:

- Locations of bio-refineries
- Optimal flow of goods

It can be stated that the expected outcomes were obtained. Optimal bio-refinery locations/capacities/technologies, intermediate/biofuel trade-flows, average fuel costs, and the distribution of costs and emissions were determined for all 18 scenarios. It is intended to reflect on all the mentioned results. In section 9.5, results from the studied scenarios were already compared.

Starting with the optimal location of bio-refineries. It has been shown that the spatial distribution of demand has a major influence on optimal bio-refinery locations. For the European scenario, the main refinery hubs are situated in Western and Southern Europe. For the Most-Likely scenario, additional refineries are built in the Northern America region. In the world scenario, Eastern Asia and Oceania are chosen as additional bio-refinery hubs. Hence, it is evident that bio-refineries are being placed near the locations of demand. The reason to place bio-refineries near the demand locations is that it is favorable to source biomass locally. Taking this as an input, figure 10.1 compares the biomass available in Europe (excluding Eastern Europe and Russia) after deduction of estimated competing uses and the amount of biofuel required to reach the RED II targets. It should be noted that a conversion yield from biomass to biofuel is not yet included. Assuming a conversion yield of around 0.6, there seems to be enough biomass in Europe to supply the maritime industry and competing industries. However, the effect of increasing biomass supply on costs should be taken into consideration. Biomass becomes increasingly difficult to collect, till at a certain point it becomes more beneficial to import resources from other regions.

The resulting intermediate bio-energy trade-flows do mainly consist of oils and fats. Most of the other feedstocks can be sourced locally. When looking at the world scenario, total import and export volumes are halved for the high supply scenario compared to the low supply scenario. The increased domestic availability of waste oils leads to fewer import dependencies. This seems to match current trading patterns. The limited availability of waste oils in Europe drastically drives up imports from other regions.

Resulting from the supply chain optimization, a marginal cost curve was drawn for each scenario to visualize the trade-off between economic and environmental performance. Emission savings were found to be in the range of 68%-95% compared to HFO with fuel costs ranging between 900-2300 EU/ton. Costs of GHG reduction till 80% are low. Reaching GHG emission savings above 80% compared to HFO drives up the costs

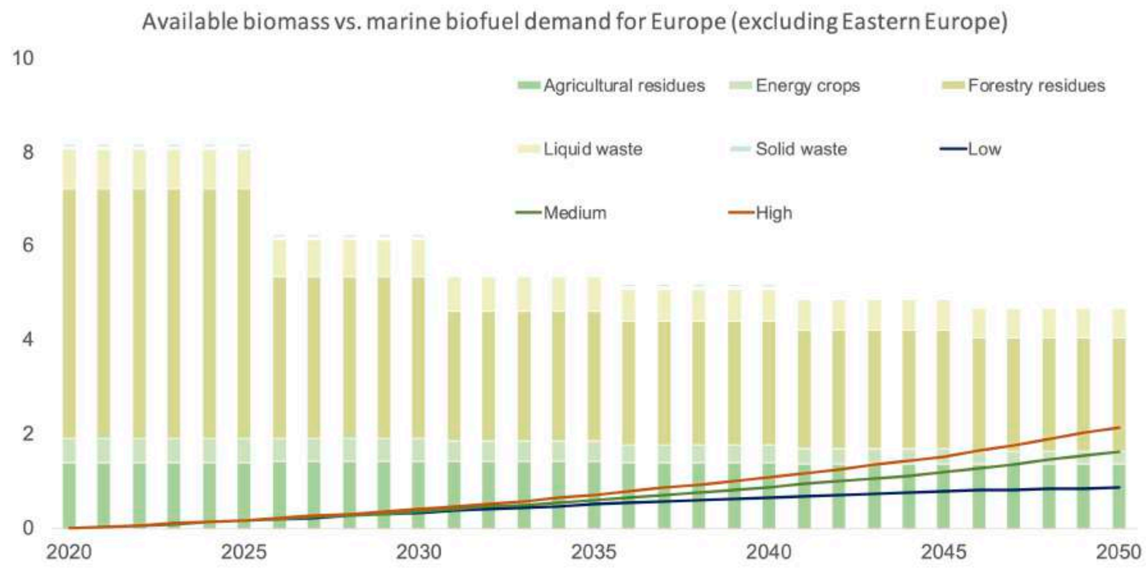

Figure 10.1: Comparison of estimated biomass availability in Europe and amount of biofuel required to reach the RED II targets in the Europe scenario. The biomass availability excludes Eastern Europe and Russia.

significantly and also influences the choice of technology. Average biofuel costs were found to increase when demand rises. As said before, the relationship between supply, demand and fuel price was not taken into account. Hence, the reason for the influence of demand on biofuel price was found to be the need for the usage of feedstocks that are more difficult to access and gather. Therefore, it could be argued that biofuels could be the victim of their success. This effect should be taken into account. Especially when comparing biofuel with synthetic fuels, for which a relationship between growing demand and feedstock costs is not applicable. As yet stated, technological learning was not included. Technological learning effects could increase efficiency and consequently drive down production costs. This effect was already discussed in section 10.2.

Besides fuel costs, it was found that the upgrading of the intermediate bio-energy carrier to a transport worthy fuel is accountable for about 80%-90% of Well-to-Tank GHG emissions and about 30% of the fuel costs. These findings are in correspondence with the literature. When reflecting on these results, the question arises whether upgrading is a requirement for the maritime industry. Tanzer [126] stated that upgrading of bio-crude from HTL is unnecessary for the purpose of a marine fuel. This topic is further addressed in the recommendations 11.2.

10.4. Reflection on the wider implications of this research

In this section the wider implications of the results from this study will be elaborated on. This consists out of suggestions for various stakeholders concerning the large scale implementation of biofuels in the maritime industry. Additionally, this section elaborates a bit more upon the availability of oils ans fats.

10.4.1. Implications for policy makers

It was initially stated that the large scale implementation of drop-in biofuels would require significant investments from which it is not sure whether they will pay off in the long run. Additionally, it was unknown where investments in new bio-refineries should take place. Using the findings presented in this thesis, it is attempted to create some guidance to this problem.

The GHG reduction targets proposed by the EU and the IMO are ambitious. The required efforts for reaching these targets using drop-in biofuels were explored. Figure 10.2 shows the refinery capacity per region required to reach these targets.

Figure 10.2: Refinery capacities required to reach the proposed targets.

Whether the bio-refinery capacities shown in figure 10.2 can be realized in the proposed time frame is dependent on the commercialization rate of lignocellulosic and waste based biofuel. Hence, rapid development of these technologies is essential to reach the quotas required to reach the GHG reduction targets. Scalability of oil and fats based biofuels is limited, which is further discussed in section 10.4.3.

It was observed that sourcing domestic biomass residue streams is beneficial, both from an economic and environmental point of view. This is also reflected in figure 10.3, which shows that biofuels are traded in larger volumes compared to the intermediate products. Hence, domestic biomass is mostly used to cover domestic demand. However, when the limited regional availability of biomass induces the need for trade, it was found to be more beneficial to firstly process the biomass in a more energy dense intermediate product. Seeing that biomass is mostly distributed over large areas of land, significant investments in distributed processing facilities are required. Analogous to the fossil supply chain, so-called bio-refineries could be placed near the demand, forming refinery hubs.

It was often mentioned in this study that besides emission reduction targets, no actual regulations for deceleration of GHG emissions are present in the shipping industry. With the FuelEU Maritime initiative, efforts are made to ensure new policy measures in the nearby future. Most stakeholders indicate that it would be preferable to regulate the shipping industry on a global level. One of the policy measures mentioned in the FuelEU Maritime initiative is the implementation of a prescriptive blending requirement. In this thesis, several scenarios for the implementation of such a prescriptive blending requirement were studied. It was found that at this stage, the only commercial renewable fuels are FAME and HVO. Due to the limited availability of vegetable and waste oils and the associated sustainability risks, possible admixture rates till 2025 were found to be in the range of 0.6%-6%, dependent on the considered supply and demand scenario. When additional technologies become available, the admixture rates can be raised and it would be possible to achieve the proposed targets of the EU and IMO. However, this would require significant investments in new bio-refineries, and rapid development of new technologies.

It was observed that an increase in demand could eventually lead to an increase in feedstock costs. This is something to take into account. Growing demand could involve the need for feedstocks that are more and more difficult to access. The availability of sustainable and efficient feedstocks is pointed out to be the main challenge in this regard. Neste, the largest producer of HVO, indicates that "additional feedstock volumes may become available as a result of improved, more sustainable agricultural practices, such as winter cropping, silvopasture, and cultivating crops on severely degraded or abandoned land" [4].

Although there are significant challenges ahead, biofuels are at this stage the only solution that is available for shipping. Especially when the upgrading phase could be (partly) skipped, advanced drop-in biofuels offer a significant emission reduction potential for the shipping industry. Therefore, on the demand side, it is advised to, implement prescriptive blending requirements for renewable fuels in the shipping industry, preferably on a global level, to increase their uptake. Starting with a modest admixture rate and gradually scaling up when new feedstock technology combinations become commercially available. On the supply side, the production capacity of advanced biofuels needs to be scaled up. This is essential for allowing efficient quotas to be set to reach the proposed emission reduction targets.

10.4.2. Implications for shipowners

It is often mentioned that shipowners take on a wait and see attitude towards the transition to renewable fuels [34]. The main cause for this attitude is the need for long term investments based on an uncertain future. Drop-in biofuels take away part of this uncertainty, seeing that no vessel modifications are required. The price gap between drop-in biofuels and fossil fuels is still significant. Nevertheless, the costs of drop-in biofuels compared to other fuels like renewable ammonia and hydrogen seem to be modest.

Shipping is a very competing industry and shipowners can therefore not afford the usage of fuels that are much more expensive as that of their competitors. Hence, the only way to stimulate the use of renewable fuels is by prescriptive regulations that ensure a level playing field. Therefore, adequate policy mechanisms are essential to bridge the price gap and increase biofuel supply capacity.

Nevertheless, shipowners should try to innovate and take matters in to own hands. Although in low blends, it is at this stage already possible to use biofuels and reduce emissions. In the Netherlands, there are already incentives that offer the opportunity to bunker biofuel for Marine Gas Oil (MGO) parity. To introduce the large scale use of biofuels, collaboration between all involved stakeholders is essential. Policy makers, shipowners, fuel suppliers and engine manufacturers should join forces to come up with effective solutions to decrease the use of fossil fuels.

10.4.3. On the limited availability of oils and fats

Many others identified the limited availability of oil crops for the production of biofuels. This shortage was acknowledged in this study and showed a barrier to the achievement of the proposed targets. The demand for biofuels made from oils and fat of the aviation and road industry constitutes severe competition for the marine sector. Without incentives for the use of biofuels in shipping, the aviation and road sectors offer more value for the same product. Consequently, the price gap that was discovered might be less of a barrier for aviation and road than for marine.

If shipping were to be included in the RED II or IMO targets, a significant amount of renewable fuel would already be required in the period 2020-2025 (about 4% for RED II and 9%-18% for IMO). Taking the expectation into account that only FAME and HVO are commercially available in that period, it would not be possible to be in line with any of the mentioned targets. Table 10.2 shows the maximum contribution of oil and fat based biofuels to the emission reduction targets for marine. Hence, after the commercial introduction, a significant jump in refinery capacity of advanced biofuels like Fast-Pyrolysis (FP), Hydrothermal Liquefaction (HTL) and Gasification Fischer-Tropsch (GFT) would be required to reach the RED II and IMO targets.

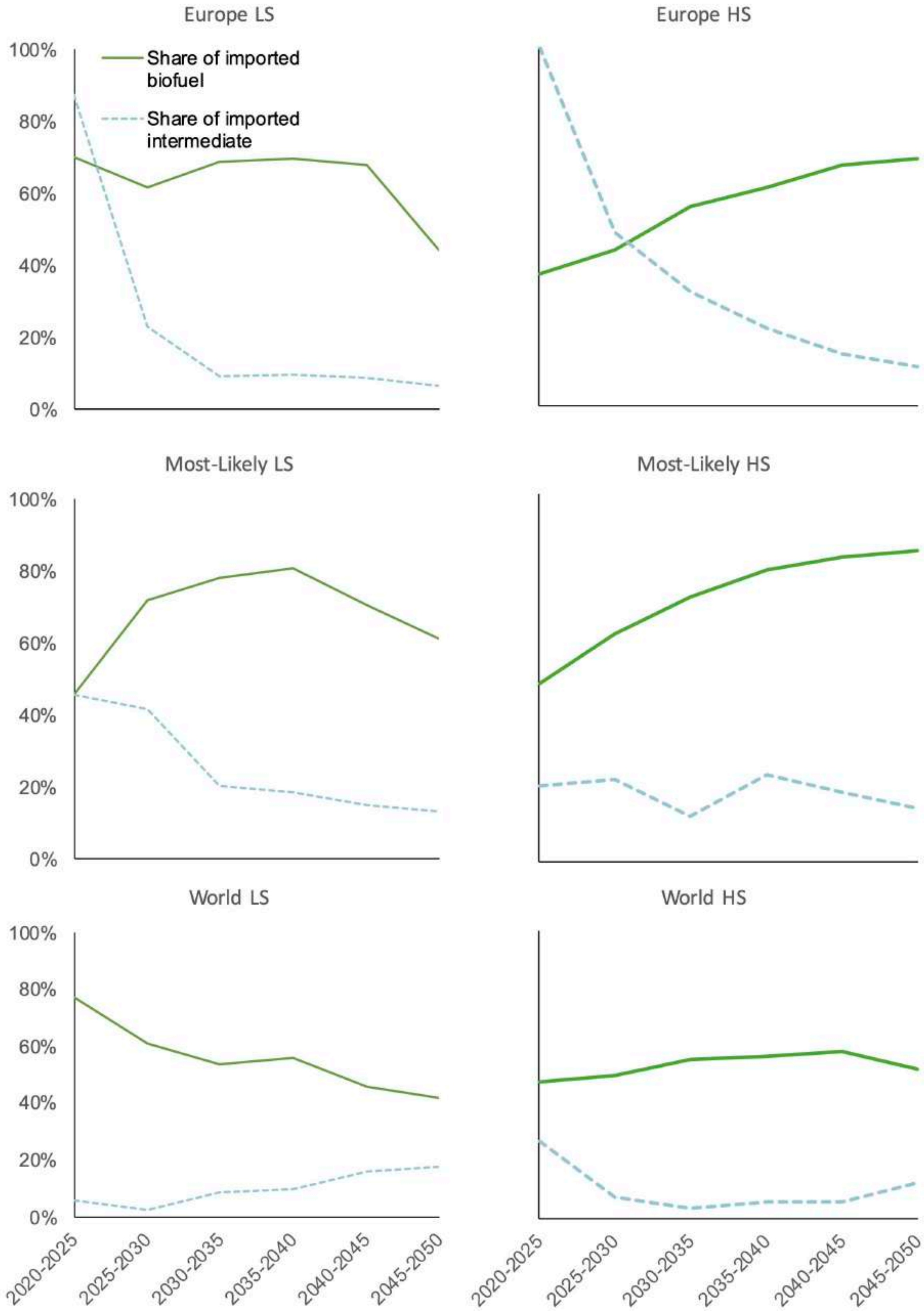

Figure 10.3: These figures indicate the share of intermediate products and biofuel that are imported.

Table 10.2: Share of required emission reductions that can be achieved using oils and fats between 2020-2025.

		Low Supply (LS)	**High Supply (HS)**
		In the LS scenario, production growth of vegetable oils based on FAO. This contains conservative waste oil availability estimations. Bio-diesel consumption of road sector grows with 2% per year. Aviation complies with renewable fuel target of IEA.	Production growth of vegetable oils is assumed to be twice as large compared to the LS scenario. This scenario contains optimistic waste oil availability estimations and electrification of the road sector happens at a fast pace.
Europe	**LD**	54%	100%
	BD	53%	100%
	HD	52%	100%
Most Likely	**LD**	41%	100%
	BD	41%	100%
	HD	39%	100%
World	**LD**	5%	48%
	BD	6%	68%
	HD	3%	33%

10.4.4. On the large scale imports of waste oils

An additional issue on the current use of oils and fats is observed due to the growing demand for waste oils. The introduction of the RED by the European Commission caused a rise in the demand for waste oils for the production of biodiesel. Currently, a significant part (around 10-20 %) of total biodiesel production is based on UCO. It is often stated that UCO based biodiesel leads to high savings in carbon intensity. The rising demand combined with the limited availability of UCO in Europe causes rising import streams from China (34%), Malaysia (12%), and Indonesia (7%) [54].

These increasing imported volumes of UCO start to raise several concerns among critics. These concerns are based on three pillars [52]:

1. Sustainability
2. Traceability
3. Quality

Firstly, one can argue that increasing UCO imports from China, Malaysia, and Indonesia causes ILUC. This statement builds on the assumption that UCO exports from China pull away uncontaminated vegetable oils from the animal feed industry, which needs to be replaced. This phenomenon induces the need for additional oil, which is allegedly fulfilled with rising palm oil imports from Malaysia and Indonesia to China. This argument is supported by the rapidly increasing palm oil imports to China. Hence, growing UCO trade flows from China to Europe raise concerns about the carbon intensity of this feedstock. Non-waste/contaminated vegetable oils are allegedly included in the UCO waste streams from China, which leads to increased palm oil imports to China for animal feed, which in turn leads to severe ILUC.

Some argue that all UCO imported to Europe needs to comply with certification schemes approved by the European Commission, and therefore the above-raised concern is ungrounded. Douglas [52] counters this argument, indicating that current anti-fraud mechanisms are soft. Only large producers need to provide samples, however, for smaller UCO collectors only a self-signed declaration is required. Douglas [52] indicates that the combination of a price spread between UCO and crude palm oil, and the soft anti-fraud mechanism causes high incentives for fraud.

Lastly, due to increasing palm oil shares in imported UCO, the resulting biodiesel obtains a lower pour point of around 23.5 degrees Celsius. Without the addition of cold flow improvers, this could lead to gelling in cold temperatures [52].

10.5. Societal relevance

This study provided insight into the means necessary to achieve the emission reduction targets proposed by RED II and the IMO as if shipping were included. It seems undisputed that more stringent regulations are required to achieve the desired emission reductions in the shipping sector. The emission reduction potential of biofuels was clarified. Additionally, the potential supplying and consuming regions of biomass were identified for several scenarios. Results from this study could help regulatory authorities with decision making on future regulations and targeted investments in new infrastructure.

Furthermore, the various studied scenarios showed the influence of the distribution of spatial demand on optimal bio-refinery locations and associated trade-flows. It was shown that significant trade of intermediate bio-energy carriers is required to fulfill the expected demand. Since low-density biomass is distributed over large areas of land, a supply chain in which many small processing facilities are located near to the feedstock source is preferred. Analogous to the petroleum supply chain, larger upgrading facilities should be situated near to the demand, which is often in major ports.

When proposing prescriptive blending requirements, the limited availability of oils and fats should be taken into account. This entails that until advanced biofuel technologies become commercial, only small admixture rates should be used to prevent severe ILUC. When lignocellulosic feedstocks can be used, these blending requirements can be significantly raised.

An additional societal advantage of the transition to renewable fuels is the creation of jobs. Especially the potential imports from biomass rich regions could lead to the existence of many new opportunities for the local community. Also, the use of lignocellulosic materials could improve the productivity and efficiency of forestry management and agricultural practices.

10.6. Scientific relevance

To identify the scientific relevance of this research, it is observed whether it is possible to fill the knowledge gap which was described in section 3.5. The gap that was addressed can be summarized in the following items.

- The spatial distribution of biomass supply was unknown.
- The future demand for marine biofuels was uncertain.
- It was unknown how future supply and demand for marine biofuels would align.
- It was unknown what the potential of marine biofuels for reaching the desired emission reduction targets could be.

Firstly, a thorough literature assessment was performed to estimate the availability of biomass per feedstock type and region. Additionally, the share of biomass use of the main competing users was estimated and deducted from the total availability. To capture the embedded uncertainty, two supply scenarios were constructed. This gave a clear idea of the bandwidth of potential regional biomass supply for each region.

Secondly, the future demand for marine biofuels was determined by taking into account two factors. The prediction of absolute energy demand from the shipping sector was split up into three scenarios, based on the Third GHG study of the IMO. The estimated share of biofuel in the total fuel mix was based on the necessary means to comply with the RED II and IMO targets.

Thirdly, a MILP model was developed to align the 18 supply and demand scenarios. This provided insight into the optimal bio-refinery locations and trade-flows. To clarify the influence of various parameters on the optimal solution, a comprehensive sensitivity analysis was executed.

Lastly, using the results from the scenario analysis, the potential of marine biofuels for the achievement of the considered targets was confirmed. Required investments in infrastructure, future estimates of fuel costs, and emissions were provided. This revealed that the potential of marine biofuels is highly dependent on the commercialization rate of technologies that make use of lignocellulosic and waste feedstocks. When this happens, the potential for biofuels to reduce GHG emissions is enormous.

11

Conclusions and recommendations

11.1. Conclusions

Following from the emission forecast of the IMO, emissions from shipping are increasing [124]. This induces the need for solutions that decelerate emissions from shipping. Alternative fuels are essential in achieving the targets set out by the IMO and the EU. However, many of these alternative fuels are not technologically mature or require significant vessel modifications. Therefore, the purpose of this thesis was to look into the long term potential of drop-in biofuels for the shipping industry. Drop-in biofuels offer the possibility to maintain the existing fuel infrastructure. Biofuels produced from oils and fats, like FAME and HVO, are already commercial at this stage. Other drop-in biofuels could become commercial if sufficient investments are made in these technologies.

However, some barriers come along with the large scale use of biofuels. Barriers include feedstock availability, technological development, and sustainability. To figure the potential of drop-in biofuels for the maritime industry, the following main research question was formulated:

"To what extent will drop-in biofuels be able to economically realize the intended local and global emission reductions for the shipping industry between 2020 and 2050?"

To answer the main research question, five sub-research questions were developed, for which the answers are summarized in table 11.1.

To decelerate climate change, drop-in biofuels should significantly reduce emissions. Additionally, they should be affordable while doing so. During the strategic supply chain optimization, both economic and environmental performance were considered.

The resulting economic performance of drop-in biofuels showed a significant price gap with current fossil fuels. The average purchase price of HFO and MGO amounts about 280 and 330 EU/ton [8]. The average production costs of biofuels were in this thesis determined to be between 900-1200 EU/ton. However, when comparing biofuels to renewable alternatives, the determined fuel costs seem to be in the lower range. Target costs for green hydrogen are in the range of 42-50 EU/GJ compared to 20-27 EU/GJ for biofuels determined in this study [68].

From the cost analysis it became apparent that biofuels could be the victim of their success. While increasing production volumes could decrease fuel costs, it also induces the need for feedstocks that are increasingly difficult to access and collect. In contrast to fossil products, which can be gathered by drilling at one centralized location, biomass can be spread across acres of land. These increasing efforts could lead to increasing feedstock costs, potentially driving up the fuel price.

The environmental performance of biofuels was found to be dependent on the price one is willing to pay. GHG emission reductions of 70-95 % compared to HFO can be achieved. However, a cost tipping point exists around 80 % GHG reduction compared to HFO. From that point on, the marginal costs of GHG reduction increase rapidly.

The limited availability of oil crops seems to be a significant barrier to the production of current commercial biofuel technologies. It was shown that the projected availability of oils and fats does not suffice for being on track with the IMO targets in each of the supply scenarios. In the Low Supply (LS) scenario, non of the proposed emission reduction targets could be met until 2025. In the High Supply (HS) scenario, compliance with the RED II targets until 2025, while only using oils and fat based biofuels, was considered possible. This should raise awareness about the need for fast development and up-scaling of new technologies, which is required to reach these targets. Until advanced biofuel technologies become commercial, possible prescriptive blending requirements for shipping are in the order of 0.6%-6%, dependent on the spatial introduction of these regulations.

Additionally, it was discovered that the spatial distribution of marine biofuel demand has a significant impact on the most feasible locations of new bio-refinery hubs and associated imports and exports of intermediate and end products. Northern America, Southern Europe, and Western Europe were found to be the most beneficial bio-refinery locations. In the global scenario, Eastern Asia and Oceania were added to this list. The most feasible deployment of technologies was found to be a mix in which Hydrothermal Liquefaction (HTL) prevails.

The conclusions from this research underpin the enormous efforts that are required to reach the proposed emission reduction targets by 2030 and 2050. Collaboration between all stakeholders is essential for achieving these targets. To speed up this process, targeted incentives for the use of sustainable fuels are required in combination with a rapid commercialization of new technologies.

Table 11.1: Answers on the initially proposed research questions.

Sub-research question	Method	Answer
1) How are biofuel supply chains previously studied and modeled?	Literature review	Biofuel supply chains were found to be mostly modeled using a MILP approach. In this thesis, a multi-objective MILP model is developed on a strategic level.
2) Where are the in-scope feedstocks located and how much is there available for the production of marine biofuel?	Data driven approach	Biomass is available all around the world but is not evenly distributed. Additionally, the future availability of biomass is uncertain and dependent on many factors. To capture this uncertainty, two supply scenarios were developed. It was found that enough biomass from residue streams could be available for the production of marine biofuels, now and in the future. The availability of oils and fats was found to be limited, as the road and aviation industry can create more value out of these feedstocks.
3) What will be the impact of different future regulatory scenarios on marine biofuel demand?	Data driven approach	Future demand for marine biofuel was found to be dependent on the growth of the shipping industry and the associated policy context. Seeing that shipping is at this stage not included in a policy context that incentives the use of renewable fuels, it was clarified what the required efforts are to reach the RED II and IMO targets. For this purpose, 9 demand scenarios were developed.
4) What are the economic, environmental and technological parameters that are required for the strategic supply chain optimization?	Data driven approach	All technological, environmental, economical and geographical parameters were estimated based on/taken from a large number of literature sources. The effect of uncertainties in these parameters on the results were exposed using a sensitivity analysis.
5) What are the most feasible future bio-refinery locations and what is the required regional capacity?	Scenario analysis	The MILP model was used to simulate the supply and demand scenarios. For the Europe scenario, the refinery hubs were found to be Southern and Western Europe. In the Most-Likely scenario, Northern America was added to this list. In the World scenario, Eastern Asia and Oceania were added. Required refinery capacities to reach the proposed targets grew from 0.1 EJ/year between 2020-2025 to 1.55 EJ/year in 2045-2050 for the Europe scenario. For the Most-Likely scenario, the required capacity grew till 2 EJ/year in 2045-2050. The required capacity for reaching the IMO targets was significantly larger, growing from 0.1 EJ/year in 2020-2025 to 13.2 EJ/year in 2045-2050.

11.2. Recommendations for further research

It is intended to further expand the knowledge obtained from this research. Therefore, this section contains several recommendations for further research and expansion of the proposed optimization model.

First of all, let us look at the model itself and identify areas of improvement and potential additional features. It was already explained that several parts of the model were modeled exogenously. Hence, an improvement would be to model the relationship between supply and demand more dynamic and endogenously. This would offer the opportunity to study potential fluctuations in fuel prices over time. Besides a dynamic interaction between supply and demand, the inclusion of technological learning effects could also be considered. De Wit et al. [47] looked into technological learning effects for this purpose. Hence, including elements of that study in the optimization model could provide even more realistic outcomes. Taking technological learning into account goes hand in hand with improving the refinery modeling. In this study, refineries were modeled as a black box, receiving input and providing output, determined by conversion yields. Outcomes from process-level studies of refineries were used to determine these conversion yields.

It was discovered during the sensitivity analysis that conversion yields have the most significant impact on total system costs and emissions. Therefore, more detailed modeling of the refineries could lead to increased confidence in the model output. Additionally, the possibility of closing refineries when a diminished utilization rate causes profit losses should be implemented. Another sub-model that could be improved is transporting. Different trade lanes, with different typical shipment sizes, vessel types, and utilization rates could be implemented. However, it was identified that transport costs and emissions only contribute to a small part of total costs and emissions.

Furthermore, the quality of the input parameters could also be improved. All input data were acquired using reliable sources and substantiated estimations. The used parameters were validated by experts from TNO and the uncertainties were addressed using scenarios and sensitivity analysis. However, it should be mentioned that several parameters like conversion yields and feedstock costs are relatively uncertain for some conversion technologies. Hence, when in the future more accurate and reliable parameter values are available, comparison with the current data would be advisable. Also, the inclusion of cost-supply curves for each region and feedstock combination is recommended.

Besides the feedstocks and conversion technologies that were considered during this thesis, it would also be possible to expand this portfolio. Other feedstocks like additional non-edible oils and algae or other conversion technologies like bio-(m)ethanol and bio-LNG could be implemented. The model framework is designed in such a way that the feedstock and fuel categorization can be changed easily.

Lastly, it was discovered that upgrading of the intermediate products to the end-products was responsible for the major part of life-cycle GHG emissions. This raises the question of whether intermediate bio-energy carriers could be used in a marine engine without upgrading. Marine engines are more robust compared to the engine configurations of the road and aviation sector. Tanzer [126] indicated in her study that bio-crude from Hydrothermal Liquefaction (HTL) could be used in a marine engine without upgrading. It is known that bio-oil from Fast-Pyrolysis (FP) is acid and corrosive. However, a slight stabilization or upgrading of this fuel might be enough to serve as a fuel for the maritime industry. The possible GHG emission savings of leaving out the upgrading phase are in the range of 80-90% of total Well to Wake emissions. Also, upgrading leads to several fractions of products, leaving only a relatively small part available for the maritime industry. Therefore, further research on this topic is greatly encouraged.

A

Optimisation literature review

This appendix contains a table in which most of the related literature in the field of biofuel supply chain optimization is shown. This table is not exclusive and significantly more literature is consulted during this thesis. It is shown that most studies used MILP modeling to study biofuel supply chains.

Table A.1: Literature review on biofuel supply chain optimisation

Author(s)	**Year**	**Pathway/feedstock**	**Model type**	**Objective**
Freppaz et al. [65]	2004	Forest biomass	MILP + GIS	Min. Costs
Tursun et al. [128]	2008	Corn grain and stover based ethanol	MILP	Min. Costs
Dunnett et al. [53]	2008	Lignocellulosic bio-ethanol	MILP	Min. Costs
Parker et al. [113]	2009		MILP	Max. Profit
Van Dyken et al. [133]	2009		MILP	Min. Costs
Leduc et al. [90]	2009	Jatropha	MILP	Min. Costs
Leduc et al. [91]	2009	Lignocellulosic residues	MILP	Min. Costs
Huang et al. [80]	2009	Waste	MILP	Min. Costs
Giarola et al. [67]	2010	Corn grain and stover	MILP	Min. Costs and Emissions
Dal Mas et al. [39]	2010	Corn residues	MILP	Max. Profit
Kim et al. [86]	2010	Forestry residues	MILP	Max. Profit
Kim et al. [85]	2010	Forestry residues	MILP	Max. Profit
Papapostolou et al. [112]	2011		MILP	Max. NPV
Akgul et al. [15]	2011	Wheat straw and miscanthus	MILP	Min. Costs
Marvin et al. [97]	2011	Lignocellulosic esidues	MILP	Max. NPV
Natarajan et al. [108]	2011	Methanol and CHP production	MILP	Min. Costs
An et al. [21]	2011	Lignocellulosic residues	MILP	Max. Profit

Akgul et al. [16]	2012	Bioethanol from various feedstocks	MILP	Min. Costs and Emissions
Lin et al. [93]	2012	Bioethanol from Miscanthus	MILP	Min. Costs
Wetterlund et al. [140]	2013	Paper mill to 2nd gen biofuel	MILP	Min. Costs
Lin et al. [94]	2013	Bioethanol from Miscanthus	MILP	Min. Costs
de Jong et al. [42]	2016		MILP	Min. Costs
Hombach et al. [74]	2016	Road	MILP	Max. NPV
de Jong et al. [43]	2018			
Conti et al. [35]	2019	Woody biomass	MILP	Min. Costs
Huang et al. [79]	2019	Corn stover	MILP	Min. Costs and Emissions
Delkhosh and Sadjadi [49]	2019	Algae		Min. Costs and Emissions
Sharifzadeh et al. [119]	2015	Lignocellulosic residues	MILP	Max. NPV

B

Supply scenarios

This appendix contains supporting information regarding the development of the used supply scenarios. This includes calculations and values used for the supply scenarios. The method for determining biomass supply from figure B.1 was already discussed in chapter 5.

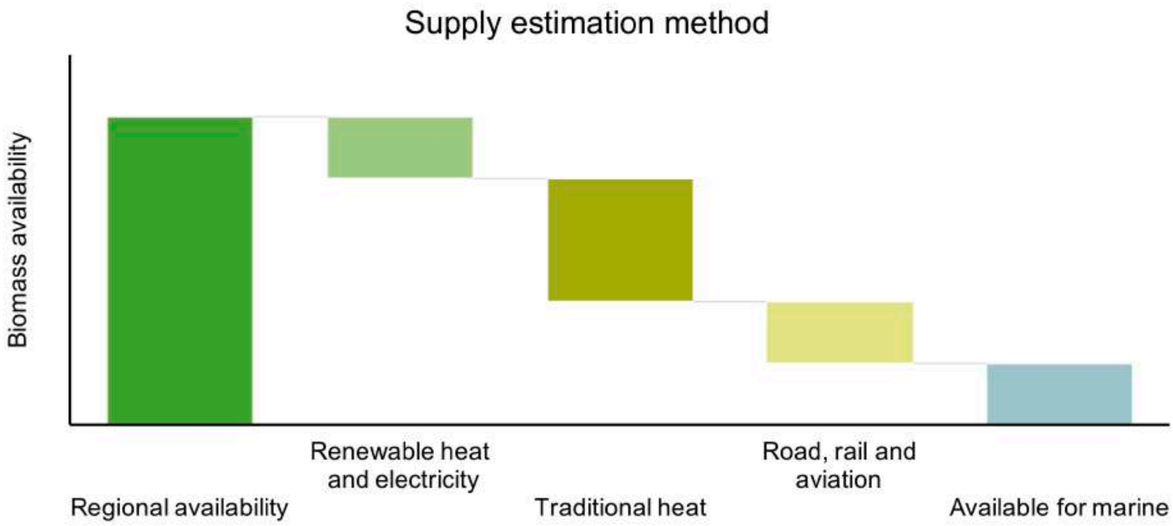

Figure B.1: Method used for determining available biomass supply.

The regional availability part is determined in section B.1. The studied competing users are identified in section B.2. What is left after deduction of the competing users is shown in sections B.3 and **??** or the low and high supply scenario respectively. When availability of a certain feedstock in a certain region becomes negative after deduction of the competing users, it is set to zero.

B.1. Feedstock availability

B.1.1. Oil crops

Table B.1: Estimated availability of vegetable oils in 2020. Data obtained from FAO.

Sub region	Vegetable oil production (kt)	Imports (kt)	Exports (kt)	Net availability (kt)	Use for domestic food (kt)	Left for energy use (kt)	Vegetable oil production rate	Sustainable amount of vegetable oil available for fuel (EJ)
Eastern Africa							25%	0,00
Middle Africa							6%	0,00
Northern Africa	6791	10162	1148	15805	16486	-681	3%	0,00
Southern Africa							29%	0,00
Western Africa							37%	0,00
Northern America	17057	4695	4584	17168	14386	2782	100%	0,10
Central America	25557	4686	10711	19532	12758	6774	1%	0,00
South America							99%	0,25
Central Asia							1%	0,01
Eastern Asia							25%	0,12
Southern Asia	111303	44957	49565	106695	93460	13235	19%	0,10
South-eastern Asia							53%	0,26
Western Asia							2%	0,01
Oceania	1240	349	820	769	824	-55	100%	0,00
Eastern Europe						12265	74%	0,34
Northern Europe	27643	13045	9882	30806	18541		5%	0,02
Southern Europe							6%	0,03
Western Europe							14%	0,07

Table B.2: Assumed growth of production and consumption, based on the FAO oilseed outlook.

	Growth (low scenario)			Growth (high scenario)		
	Production growth	**Consumption growth**	**Net growth**	**Production growth**	**Consumption growth**	**Net growth**
Eastern Africa	3,5%	2,9%	0,6%	7,0%	2,9%	4,1%
Middle Africa	3,5%	2,9%	0,6%	7,0%	2,9%	4,1%
Northern Africa	3,5%	2,9%	0,6%	7,0%	2,9%	4,1%
Southern Africa	3,5%	2,9%	0,6%	7,0%	2,9%	4,1%
Western Africa	3,5%	2,9%	0,6%	7,0%	2,9%	4,1%
Northern America	2,5%	0,8%	1,8%	5,0%	0,8%	4,3%
Central America	3,5%	0,7%	2,8%	7,0%	0,7%	6,3%
South America	4,0%	0,7%	3,3%	8,0%	0,7%	7,3%
Central Asia	3,5%	2,2%	1,3%	7,0%	2,2%	4,8%
Eastern Asia	3,5%	2,2%	1,3%	7,0%	2,2%	4,8%
Southern Asia	3,5%	2,2%	1,3%	7,0%	2,2%	4,8%
South-eastern Asia	3,5%	2,2%	1,3%	7,0%	2,2%	4,8%
Western Asia	3,5%	2,2%	1,3%	7,0%	2,2%	4,8%
Oceania	3,5%	2,0%	1,5%	7,0%	2,0%	5,0%
Eastern Europe	4,0%	0,3%	3,7%	8,0%	0,3%	7,7%
Northern Europe	1,5%	-0,3%	1,8%	3,0%	-0,3%	3,3%
Southern Europe	1,5%	-0,3%	1,8%	3,0%	-0,3%	3,3%
Western Europe	1,5%	-0,3%	1,8%	3,0%	-0,3%	3,3%

Table B.3: Vegetable oil availability, LS scenario.

Unit: EJ	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Eastern Africa	0,00	0,00	0,00	0,00	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,00	0,00	0,00	0,00
Western Africa	0,00	0,00	0,00	0,00	0,00	0,00
Northern America	0,55	0,60	0,66	0,72	0,78	0,85
Central America	0,02	0,02	0,02	0,03	0,03	0,04
South America	1,39	1,63	1,92	2,25	2,65	3,11
Central Asia	0,03	0,04	0,04	0,04	0,04	0,05
Eastern Asia	0,65	0,69	0,74	0,79	0,84	0,90
Southern Asia	0,50	0,53	0,57	0,61	0,65	0,69
South-eastern Asia	1,37	1,46	1,56	1,66	1,77	1,89
Western Asia	0,05	0,05	0,05	0,06	0,06	0,07
Oceania	0,00	0,00	0,00	0,00	0,00	0,00
Eastern Europe	1,92	2,30	2,76	3,30	3,96	4,75
Northern Europe	0,12	0,13	0,14	0,15	0,16	0,18
Southern Europe	0,16	0,17	0,19	0,20	0,22	0,24
Western Europe	0,35	0,38	0,42	0,46	0,50	0,55

Table B.4: Vegetable oil availability, HS scenario.

Unit: EJ	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Eastern Africa	0,00	0,00	0,00	0,00	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,00	0,00	0,00	0,00
Western Africa	0,00	0,00	0,00	0,00	0,00	0,00
Northern America	0,65	0,81	0,99	1,22	1,50	1,85
Central America	0,02	0,03	0,04	0,06	0,08	0,10
South America	1,72	2,44	3,47	4,93	7,01	9,96
Central Asia	0,04	0,05	0,06	0,08	0,10	0,13
Eastern Asia	0,79	1,00	1,26	1,60	2,02	2,56
Southern Asia	0,61	0,77	0,97	1,23	1,56	1,97
South-eastern Asia	1,67	2,11	2,67	3,37	4,27	5,40
Western Asia	0,06	0,07	0,09	0,12	0,15	0,19
Oceania	0,00	0,00	0,00	0,00	0,00	0,00
Eastern Europe	2,37	3,44	4,98	7,21	10,45	15,13
Northern Europe	0,13	0,16	0,18	0,22	0,25	0,30
Southern Europe	0,18	0,21	0,25	0,29	0,34	0,40
Western Europe	0,40	0,47	0,56	0,66	0,77	0,90

B.1.2. UCO and tallow

Table B.5: Estimated UCO availability.

	Vegetable oil consumption (kt/year)	Percentage retrievable as UCO	Percentage collected	Collected UCO (kt/year)	Collected UCO (EJ/year)
Eastern Africa	5477	15%	0%	0	0,00
Middle Africa	2208	15%	0%	0	0,00
Northern Africa	3028	15%	0%	0	0,00
Southern Africa	830	15%	0%	0	0,00
Western Africa	4942	15%	0%	0	0,00
Northern America	14386	30%	70%	3021	0,11
Central America	3755	15%	0%	0	0,00
South America	9003	15%	15%	203	0,01
Central Asia	1531	15%	0%	0	0,00
Eastern Asia	34329	30%	70%	7209	0,27
Southern Asia	37369	15%	35%	1962	0,07
South-eastern Asia	13774	15%	35%	723	0,03
Western Asia	6457	9%	30%	174	0,01
Oceania	824	15%	15%	19	0,00
Eastern Europe	7267	9%	30%	196	0,01
Northern Europe	2635	14%	70%	258	0,01
Southern Europe	3775	23%	35%	304	0,01
Western Europe	4864	15%	70%	511	0,02

Table B.6: Estimated tallow availability.

	Tallow production (ton)	Category 1 & Category 2 (%)	Category 3 (%)	Category 1 & Category 2 (ton)	Category 3 (ton)
Eastern Africa	8327	65%	35%	5413	2914
Middle Africa	0	65%	35%	0	0
Northern Africa	0	65%	35%	0	0
Southern Africa	25072	65%	35%	16297	8775
Western Africa	0	65%	35%	0	0
Northern America	3656200	65%	35%	2376530	1279670
Central America	112936	65%	35%	73408	39528
South America	999282	65%	35%	649533	349749
Central Asia	0	65%	35%	0	0
Eastern Asia	189994	65%	35%	123496	66498
Southern Asia	136918	65%	35%	88997	47921
South-eastern Asia	2921	65%	35%	1899	1022
Western Asia	4491	65%	35%	2919	1572
Oceania	751808	65%	35%	488675	263133
Eastern Europe	71275	65%	35%	46329	24946
Northern Europe	204885	65%	35%	133175	71710
Southern Europe	73490	65%	35%	47769	25722
Western Europe	396529	65%	35%	257744	138785

Table B.7: Projected UCO availability (HS scenario).

Unit: EJ	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Eastern Africa	0,00	0,00	0,00	0,00	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,00	0,00	0,00	0,00
Western Africa	0,00	0,00	0,00	0,00	0,00	0,00
Northern America	0,60	0,67	0,74	0,81	0,90	0,99
Central America	0,00	0,00	0,00	0,00	0,00	0,00
South America	0,04	0,04	0,05	0,05	0,06	0,07
Central Asia	0,00	0,00	0,00	0,00	0,00	0,00
Eastern Asia	1,44	1,59	1,76	1,94	2,14	2,37
Southern Asia	0,39	0,43	0,48	0,53	0,58	0,64
South-eastern Asia	0,14	0,16	0,18	0,19	0,21	0,24
Western Asia	0,03	0,04	0,04	0,05	0,05	0,06
Oceania	0,00	0,00	0,00	0,00	0,01	0,01
Eastern Europe	0,04	0,04	0,05	0,05	0,06	0,06
Northern Europe	0,05	0,06	0,06	0,07	0,08	0,08
Southern Europe	0,06	0,07	0,07	0,08	0,09	0,10
Western Europe	0,10	0,11	0,12	0,14	0,15	0,17

Table B.8: Projected tallow availability (HS scenario).

Unit: EJ	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Eastern Africa	0,00	0,00	0,00	0,00	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,00	0,00	0,00	0,00
Western Africa	0,00	0,00	0,00	0,00	0,00	0,00
Northern America	0,43	0,43	0,43	0,43	0,43	0,43
Central America	0,01	0,01	0,01	0,01	0,01	0,01
South America	0,12	0,12	0,12	0,12	0,12	0,12
Central Asia	0,00	0,00	0,00	0,00	0,00	0,00
Eastern Asia	0,02	0,02	0,02	0,02	0,02	0,02
Southern Asia	0,02	0,02	0,02	0,02	0,02	0,02
South-eastern Asia	0,00	0,00	0,00	0,00	0,00	0,00
Western Asia	0,00	0,00	0,00	0,00	0,00	0,00
Oceania	0,09	0,09	0,09	0,09	0,09	0,09
Eastern Europe	0,01	0,01	0,01	0,01	0,01	0,01
Northern Europe	0,02	0,02	0,02	0,02	0,02	0,02
Southern Europe	0,01	0,01	0,01	0,01	0,01	0,01
Western Europe	0,05	0,05	0,05	0,05	0,05	0,05

B.1.3. Agricultural residues

Table B.9: Estimated agricultural residue availability.

	Share per region	Low global potential (EJ/year)	High global potential (EJ/year)	Low global potential (EJ/year)	High global potential (EJ/year)	Share of agricultural cultivation	Agricultural residues low-high (EJ/year)	
Eastern Africa						30%	0,95	1,69
Middle Africa						7%	0,23	0,40
Northern Africa	9%			3,19	5,69	22%	0,71	1,27
Southern Africa						8%	0,26	0,47
Western Africa						33%	1,05	1,87
Northern America	13%			4,93	8,79	100%	4,93	8,79
Central America	14%			5,27	9,39	10%	0,53	0,94
South America						90%	4,74	8,45
Central Asia		36,8	65,6			3%	0,49	0,87
Eastern Asia						46%	8,21	14,64
Southern Asia	49%			18,03	32,14	29%	5,20	9,27
South-eastern Asia						19%	3,50	6,23
Western Asia						4%	0,64	1,13
Oceania	2%			0,73	1,30	100%	0,73	1,30
Eastern Europe						57%	2,66	4,74
Northern Europe	13%			4,65	8,29	8%	0,38	0,69
Southern Europe						14%	0,63	1,12
Western Europe						21%	0,98	1,74

Table B.10: Projected availability of agricultural residues (LS scenario).

Unit: EJ	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Eastern Africa	4,01	4,52	5,01	5,51	6,05	6,65
Middle Africa	0,95	1,07	1,19	1,31	1,44	1,58
Northern Africa	3,23	3,47	3,66	3,83	4,00	4,19
Southern Africa	1,11	1,25	1,38	1,52	1,67	1,83
Western Africa	4,43	4,99	5,54	6,08	6,68	7,34
Northern America	23,31	24,26	24,87	25,24	25,62	26,01
Central America	2,34	2,55	2,69	2,78	2,88	2,98
South America	21,06	22,91	24,20	25,05	25,94	26,86
Central Asia	2,19	2,36	2,50	2,62	2,74	2,86
Eastern Asia	38,03	40,17	41,42	42,05	42,68	43,33
Southern Asia	23,44	25,25	26,72	27,95	29,23	30,57
South-eastern Asia	15,75	16,97	17,96	18,78	19,64	20,54
Western Asia	2,89	3,09	3,26	3,39	3,53	3,67
Oceania	3,44	3,58	3,67	3,73	3,79	3,84
Eastern Europe	12,56	13,08	13,40	13,61	13,81	14,02
Northern Europe	1,82	1,89	1,94	1,97	2,00	2,03
Southern Europe	2,98	3,10	3,18	3,23	3,28	3,33
Western Europe	4,62	4,81	4,93	5,00	5,08	5,16

Table B.11: Projected availability of agricultural residues (HS scenario).

Unit: EJ	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Eastern Africa	7,16	8,06	8,94	9,82	10,79	11,85
Middle Africa	1,70	1,92	2,13	2,34	2,57	2,82
Northern Africa	5,76	6,18	6,52	6,82	7,14	7,46
Southern Africa	1,97	2,22	2,47	2,71	2,98	3,27
Western Africa	7,90	8,90	9,87	10,85	11,92	13,09
Northern America	41,55	43,24	44,33	45,00	45,68	46,37
Central America	4,17	4,54	4,79	4,96	5,14	5,32
South America	37,55	40,85	43,13	44,66	46,25	47,89
Central Asia	3,91	4,21	4,46	4,66	4,88	5,10
Eastern Asia	67,79	71,60	73,84	74,96	76,09	77,23
Southern Asia	41,79	45,02	47,64	49,82	52,10	54,49
South-eastern Asia	28,08	30,25	32,01	33,48	35,01	36,62
Western Asia	5,14	5,51	5,81	6,04	6,29	6,54
Oceania	6,14	6,39	6,55	6,65	6,75	6,85
Eastern Europe	22,40	23,31	23,89	24,26	24,62	24,99
Northern Europe	3,24	3,37	3,46	3,51	3,56	3,62
Southern Europe	5,32	5,53	5,67	5,76	5,85	5,93
Western Europe	8,24	8,57	8,79	8,92	9,05	9,19

B.1.4. Forestry residues

Table B.12: Estimated availability of forestry residues.

	Share per region	Low global potential (EJ/year)	High global potential (EJ/year)	Low global potential (EJ/year)	High global potential (EJ/year)	Share of forestry production	Forestry residues low-high (EJ/year)	
Eastern Africa						43%	0,43	0,98
Middle Africa						17%	0,17	0,39
Northern Africa	5%			1,00	2,28	7%	0,07	0,16
Southern Africa						4%	0,04	0,09
Western Africa						29%	0,29	0,66
Northern America	33%			6,98	15,95	100%	6,98	15,95
Central America	6%			1,36	3,11	18%	0,24	0,56
South America						82%	1,12	2,55
Central Asia		21,4	48,9			0%	0,01	0,03
Eastern Asia						32%	1,24	2,84
Southern Asia	18%			3,90	8,91	41%	1,60	3,66
South-eastern Asia						24%	0,94	2,15
Western Asia						2%	0,10	0,22
Oceania	6%			1,18	2,69	100%	1,18	2,69
Eastern Europe						48%	3,35	7,66
Northern Europe	33%			6,98	15,95	23%	1,61	3,67
Southern Europe						9%	0,63	1,44
Western Europe						20%	1,40	3,19

Table B.13: Projection of forestry residue availability (LS scenario).

Unit: EJ	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Eastern Africa	3,58	2,49	2,11	2,06	2,01	1,96
Middle Africa	1,42	0,99	0,84	0,81	0,79	0,77
Northern Africa	0,58	0,41	0,34	0,34	0,33	0,32
Southern Africa	0,33	0,23	0,20	0,19	0,19	0,18
Western Africa	2,42	1,68	1,42	1,39	1,36	1,32
Northern America	58,33	40,58	34,39	33,54	32,71	31,90
Central America	2,05	1,42	1,21	1,18	1,15	1,12
South America	9,32	6,48	5,49	5,36	5,23	5,10
Central Asia	0,12	0,09	0,07	0,07	0,07	0,07
Eastern Asia	10,38	7,22	6,12	5,97	5,82	5,68
Southern Asia	13,40	9,32	7,90	7,70	7,51	7,33
South-eastern Asia	7,87	5,48	4,64	4,53	4,41	4,31
Western Asia	0,80	0,56	0,47	0,46	0,45	0,44
Oceania	9,85	6,85	5,81	5,66	5,52	5,39
Eastern Europe	28,00	19,48	16,51	16,10	15,70	15,31
Northern Europe	13,42	9,33	7,91	7,71	7,52	7,34
Southern Europe	5,25	3,65	3,10	3,02	2,94	2,87
Western Europe	11,67	8,12	6,88	6,71	6,54	6,38

Table B.14: Projection of forestry residue availability (HS scenario).

Unit: EJ	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Eastern Africa	8,19	5,70	4,83	4,71	4,59	4,48
Middle Africa	3,24	2,25	1,91	1,86	1,82	1,77
Northern Africa	1,33	0,93	0,79	0,77	0,75	0,73
Southern Africa	0,76	0,53	0,45	0,44	0,43	0,42
Western Africa	5,52	3,84	3,26	3,18	3,10	3,02
Northern America	133,28	92,72	78,58	76,64	74,74	72,89
Central America	4,67	3,25	2,76	2,69	2,62	2,56
South America	21,29	14,81	12,55	12,24	11,94	11,64
Central Asia	0,28	0,20	0,17	0,16	0,16	0,15
Eastern Asia	23,72	16,50	13,99	13,64	13,30	12,97
Southern Asia	30,61	21,29	18,05	17,60	17,17	16,74
South-eastern Asia	17,99	12,51	10,61	10,34	10,09	9,84
Western Asia	1,83	1,27	1,08	1,05	1,03	1,00
Oceania	22,50	15,65	13,27	12,94	12,62	12,31
Eastern Europe	63,97	44,51	37,72	36,79	35,88	34,99
Northern Europe	30,65	21,33	18,07	17,63	17,19	16,77
Southern Europe	12,00	8,34	7,07	6,90	6,73	6,56
Western Europe	26,66	18,54	15,72	15,33	14,95	14,58

B.1.5. Energy crops

Table B.15: Estimation of energy crop availability.

	Low (EJ)	High (EJ)	Share of agricultural production	Low (EJ)	High (EJ)
Eastern Africa	5	6	28%	1,41	1,69
Middle Africa			2%	0,11	0,13
Northern Africa			26%	1,30	1,56
Southern Africa			14%	0,72	0,87
Western Africa			31%	1,57	1,88
Northern America	7	7	33%	2,34	2,34
Central America	15	16	9%	0,60	0,60
South America			58%	8,69	9,27
Central Asia	1	1	13%	0,13	0,13
Eastern Asia			41%	0,41	0,41
Southern Asia			17%	0,17	0,17
South-eastern Asia			14%	0,14	0,14
Western Asia			15%	0,15	0,15
Oceania	2	2	100%	2,00	2,00
Eastern Europe	5	6	82%	4,12	4,94
Northern Europe			7%	0,34	0,40
Southern Europe			6%	0,30	0,36
Western Europe			5%	0,25	0,30

Table B.16: Projection of energy crop availability (LS scenario).

Unit: EJ	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Eastern Africa	5,98	6,74	7,47	8,21	9,02	9,91
Middle Africa	0,46	0,51	0,57	0,63	0,69	0,76
Northern Africa	5,88	6,30	6,66	6,96	7,28	7,61
Southern Africa	3,07	3,46	3,83	4,21	4,63	5,08
Western Africa	6,64	7,48	8,29	9,11	10,01	11,00
Northern America	11,06	11,51	11,80	11,98	12,16	12,34
Central America	2,68	2,92	3,08	3,19	3,30	3,42
South America	38,64	42,04	44,39	45,97	47,60	49,29
Central Asia	0,60	0,65	0,69	0,72	0,75	0,79
Eastern Asia	1,88	1,98	2,05	2,08	2,11	2,14
Southern Asia	0,77	0,83	0,88	0,92	0,96	1,01
South-eastern Asia	0,61	0,66	0,70	0,73	0,77	0,80
Western Asia	0,69	0,74	0,78	0,81	0,85	0,88
Oceania	9,46	9,84	10,09	10,24	10,40	10,55
Eastern Europe	19,47	20,26	20,77	21,08	21,40	21,72
Northern Europe	1,59	1,65	1,69	1,72	1,74	1,77
Southern Europe	1,41	1,47	1,50	1,53	1,55	1,57
Western Europe	1,18	1,23	1,26	1,28	1,30	1,32

Table B.17: Projection of energy crop availability (HS scenario).

Unit: EJ	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Eastern Africa	7,18	8,09	8,97	9,85	11,03	11,90
Middle Africa	0,55	0,62	0,68	0,75	0,84	0,91
Northern Africa	7,06	7,56	7,99	8,35	8,82	9,14
Southern Africa	3,68	4,15	4,60	5,05	5,66	6,10
Western Africa	7,97	8,97	9,95	10,94	12,24	13,20
Northern America	11,06	11,51	11,80	11,98	12,20	12,34
Central America	2,68	2,92	3,08	3,19	3,33	3,42
South America	41,22	44,84	47,35	49,03	51,13	52,57
Central Asia	0,60	0,65	0,69	0,72	0,76	0,79
Eastern Asia	1,88	1,98	2,05	2,08	2,12	2,14
Southern Asia	0,77	0,83	0,88	0,92	0,97	1,01
South-eastern Asia	0,61	0,66	0,70	0,73	0,77	0,80
Western Asia	0,69	0,74	0,78	0,81	0,85	0,88
Oceania	9,46	9,84	10,09	10,24	10,43	10,55
Eastern Europe	23,36	24,31	24,92	25,30	25,76	26,07
Northern Europe	1,90	1,98	2,03	2,06	2,10	2,12
Southern Europe	1,69	1,76	1,80	1,83	1,87	1,89
Western Europe	1,42	1,47	1,51	1,53	1,56	1,58

B.1.6. Solid waste

Table B.18: Estimation of MSW availability for energy use.

Region	MSW generation (mln ton/year)	Solid waste disposal (%)	Solid waste disposal (mln ton/year)
Eastern Africa	129	69%	89
Middle Africa	52	69%	36
Northern Africa	71	69%	49
Southern Africa	20	69%	14
Western Africa	117	69%	80
Northern America	240	58%	139
Central America	38	50%	19
South America	112	54%	60
Central Asia	16	74%	12
Eastern Asia	617	55%	339
Southern Asia	381	74%	282
South-eastern Asia	181	59%	107
Western Asia	66	74%	49
Oceania	29	85%	25
Eastern Europe	111	90%	100
Northern Europe	68	47%	32
Southern Europe	79	85%	67
Western Europe	110	47%	52

Table B.19: Estimation of MSW availability for energy use.

Region	Food waste	Food waste	Paper/cardboard	Wood	Share living in urban areas	MSW available for energy (EJ/year)
Eastern Africa	54%	54%	8%	7%	29%	0,16
Middle Africa	43%	43%	17%	7%	51%	0,11
Northern Africa	51%	51%	17%	2%	52%	0,16
Southern Africa	23%	23%	25%	15%	65%	0,05
Western Africa	40%	40%	10%	4%	47%	0,19
Northern America	34%	34%	23%	6%	82%	0,65
Central America	44%	44%	14%	14%	75%	0,09
South America	45%	45%	17%	5%	85%	0,31
Central Asia	40%	40%	11%	8%	48%	0,03
Eastern Asia	26%	26%	19%	4%	64%	0,95
Southern Asia	40%	40%	11%	8%	36%	0,54
South-eastern Asia	44%	44%	13%	10%	50%	0,32
Western Asia	41%	41%	18%	10%	72%	0,22
Oceania	36%	36%	30%	24%	68%	0,14
Eastern Europe	30%	30%	22%	8%	69%	0,37
Northern Europe	24%	24%	31%	10%	82%	0,15
Southern Europe	37%	37%	17%	11%	72%	0,28
Western Europe	24%	24%	28%	11%	80%	0,23

Table B.20: Projected availability of MSW (LS scenario).

Unit: EJ	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Eastern Africa	0,86	0,97	1,10	1,24	1,41	1,59
Middle Africa	0,59	0,67	0,76	0,86	0,97	1,10
Northern Africa	0,86	0,98	1,11	1,25	1,41	1,60
Southern Africa	0,27	0,30	0,34	0,39	0,44	0,50
Western Africa	1,00	1,13	1,28	1,45	1,64	1,85
Northern America	3,31	3,41	3,52	3,63	3,74	3,86
Central America	0,46	0,49	0,51	0,53	0,56	0,58
South America	1,59	1,66	1,73	1,81	1,90	1,98
Central Asia	0,15	0,16	0,17	0,17	0,18	0,19
Eastern Asia	4,86	5,07	5,30	5,53	5,77	6,02
Southern Asia	2,79	2,91	3,04	3,17	3,31	3,45
South-eastern Asia	1,63	1,70	1,78	1,85	1,93	2,02
Western Asia	1,12	1,16	1,22	1,27	1,32	1,38
Oceania	0,72	0,77	0,82	0,87	0,93	0,99
Eastern Europe	1,85	1,85	1,85	1,85	1,85	1,85
Northern Europe	0,77	0,79	0,81	0,83	0,85	0,87
Southern Europe	1,40	1,39	1,39	1,38	1,37	1,37
Western Europe	1,18	1,20	1,23	1,25	1,28	1,30

Table B.21: Projected availability of MSW (HS scenario).

Unit: EJ	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Eastern Africa	0,87	1,01	1,17	1,36	1,58	1,83
Middle Africa	0,60	0,70	0,81	0,94	1,09	1,26
Northern Africa	0,88	1,02	1,18	1,37	1,58	1,84
Southern Africa	0,27	0,32	0,37	0,42	0,49	0,57
Western Africa	1,02	1,18	1,36	1,58	1,83	2,13
Northern America	3,35	3,52	3,70	3,89	4,08	4,29
Central America	0,47	0,49	0,51	0,54	0,57	0,60
South America	1,59	1,67	1,76	1,85	1,94	2,04
Central Asia	0,15	0,16	0,17	0,18	0,19	0,20
Eastern Asia	4,88	5,13	5,39	5,67	5,96	6,26
Southern Asia	2,80	2,94	3,09	3,25	3,42	3,59
South-eastern Asia	1,64	1,72	1,81	1,90	2,00	2,10
Western Asia	1,12	1,18	1,24	1,30	1,37	1,44
Oceania	0,72	0,78	0,84	0,91	0,98	1,06
Eastern Europe	1,86	1,88	1,90	1,92	1,94	1,95
Northern Europe	0,77	0,80	0,82	0,85	0,87	0,90
Southern Europe	1,41	1,41	1,41	1,41	1,41	1,41
Western Europe	1,18	1,21	1,24	1,27	1,31	1,34

B.1.7. Liquid waste

Table B.22: Estimation of animal manure availability.

	Live stock population (mln)				
	Dairy cows	**Chickens**	**Goats**	**Pigs**	**Sheep**
Eastern Africa	50,8	0,7	8,9	22,9	9,3
Middle Africa	26,1	0,1	11,2	0,9	57,3
Northern Africa	170,8	0,4	149,3	17,3	94,1
Southern Africa	75,7	5,9	169,6	470,3	194,8
Western Africa	37,8	1,1	4,8	54,3	37,1
Northern America	46,0	0,1	57,6	7,2	39,6
Central America	41,9	0,7	50,6	0,0	109,0
South America	105,9	2,1	2,7	88,7	6,1
Central Asia	23,4	0,3	0,2	24,1	42,8
Eastern Asia	37,0	0,1	4,1	5,7	97,4
Southern Asia	357,2	2,6	22,3	67,7	65,0
South-eastern Asia	52,7	3,9	31,4	77,8	19,0
Western Asia	18,2	0,2	9,8	1,7	26,1
Oceania	273,7	2,8	301,7	10,0	149,0
Eastern Europe	17,7	0,4	9,5	47,3	40,3
Northern Europe	78,8	0,5	170,9	14,3	115,3
Southern Europe	26,5	1,0	35,0	0,8	94,9
Western Europe	40,4	0,5	2,3	62,7	10,4

Table B.23: Wet manure production per region.

	Wet manure (mln ton/year)				
	Dairy cows	**Chickens**	**Goats**	**Pigs**	**Sheep**
Eastern Africa	648,4	0,0	5,1	27,6	4,9
Middle Africa	333,9	0,0	6,3	1,1	30,1
Northern Africa	2182,0	0,0	84,5	20,9	49,5
Southern Africa	967,5	0,3	96,0	566,5	102,4
Western Africa	483,1	0,0	2,7	65,4	19,5
Northern America	587,3	0,0	32,6	8,7	20,8
Central America	534,8	0,0	28,6	0,0	57,3
South America	1352,4	0,1	1,5	106,9	3,2
Central Asia	298,9	0,0	0,1	29,0	22,5
Eastern Asia	472,9	0,0	2,3	6,9	51,2
Southern Asia	4563,5	0,1	12,6	81,6	34,1
South-eastern Asia	673,5	0,2	17,8	93,7	10,0
Western Asia	233,1	0,0	5,5	2,0	13,7
Oceania	3496,3	0,1	170,7	12,1	78,3
Eastern Europe	226,3	0,0	5,4	56,9	21,2
Northern Europe	1006,9	0,0	96,7	17,2	60,6
Southern Europe	338,9	0,0	19,8	1,0	49,9
Western Europe	516,5	0,0	1,3	75,6	5,5

Table B.24: Region solid manure availability.

	Solid manure (mln ton/year)				
	Dairy cows	**Chickens**	**Goats**	**Pigs**	**Sheep**
Eastern Africa	84,3	0,0	0,5	2,5	0,5
Middle Africa	43,4	0,0	0,6	0,1	3,0
Northern Africa	283,7	0,0	8,4	1,9	4,9
Southern Africa	125,8	0,1	9,6	51,0	10,2
Western Africa	62,8	0,0	0,3	5,9	2,0
Northern America	76,3	0,0	3,3	0,8	2,1
Central America	69,5	0,0	2,9	0,0	5,7
South America	175,8	0,0	0,2	9,6	0,3
Central Asia	38,9	0,0	0,0	2,6	2,3
Eastern Asia	61,5	0,0	0,2	0,6	5,1
Southern Asia	593,3	0,0	1,3	7,3	3,4
South-eastern Asia	87,6	0,0	1,8	8,4	1,0
Western Asia	30,3	0,0	0,6	0,2	1,4
Oceania	454,5	0,0	17,1	1,1	7,8
Eastern Europe	29,4	0,0	0,5	5,1	2,1
Northern Europe	130,9	0,0	9,7	1,5	6,1
Southern Europe	44,1	0,0	2,0	0,1	5,0
Western Europe	67,1	0,0	0,1	6,8	0,5

Table B.25: Recovery rates, adapted from IRENA [83].

	Recovery rate				
	Dairy cows	Chickens	Goats	Pigs	Sheep
Eastern Africa	6%	6%	3%	6%	3%
Middle Africa	6%	6%	3%	6%	3%
Northern Africa	6%	6%	3%	6%	3%
Southern Africa	6%	6%	3%	6%	3%
Western Africa	6%	6%	3%	6%	3%
Northern America	42%	51%	0%	51%	0%
Central America	1%	8%	0%	8%	0%
South America	1%	8%	0%	8%	0%
Central Asia	51%	47%	2%	47%	2%
Eastern Asia	51%	47%	2%	47%	2%
Southern Asia	51%	47%	2%	47%	2%
South-eastern Asia	51%	47%	2%	47%	2%
Western Asia	51%	47%	2%	47%	2%
Oceania	17%	54%	0%	0%	54%
Eastern Europe	18%	3%	23%	3%	23%
Northern Europe	36%	9%	25%	9%	25%
Southern Europe	36%	9%	25%	9%	25%
Western Europe	36%	9%	25%	9%	25%

Table B.26: The potential availability of animal manure per region.

	Manure for energy (PJ/year)				
	Dairy cows	Chickens	Goats	Pigs	Sheep
Eastern Africa	75,4	0,0	0,2	2,2	0,2
Middle Africa	38,8	0,0	0,3	0,1	1,3
Northern Africa	253,6	0,0	3,8	1,7	2,2
Southern Africa	112,4	0,1	4,3	45,6	4,6
Western Africa	56,1	0,0	0,1	5,3	0,9
Northern America	477,8	0,0	0,1	6,0	0,1
Central America	10,4	0,0	0,0	0,0	0,0
South America	26,2	0,0	0,0	11,5	0,0
Central Asia	295,3	0,0	0,0	18,3	0,7
Eastern Asia	467,1	0,0	0,1	4,4	1,5
Southern Asia	4508,2	0,2	0,4	51,4	1,0
South-eastern Asia	665,4	0,3	0,5	59,0	0,3
Western Asia	230,3	0,0	0,2	1,3	0,4
Oceania	1151,3	0,2	0,0	0,0	63,0
Eastern Europe	76,7	0,0	1,8	2,3	7,1
Northern Europe	696,3	0,0	36,3	2,0	22,7
Southern Europe	234,4	0,0	7,4	0,1	18,7
Western Europe	357,2	0,0	0,5	8,8	2,1

Table B.27: Projected availability of manure (LS scenario).

Unit: EJ	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Eastern Africa	0,39	0,39	0,39	0,39	0,39	0,39
Middle Africa	0,20	0,20	0,20	0,20	0,20	0,20
Northern Africa	1,31	1,31	1,31	1,31	1,31	1,31
Southern Africa	0,83	0,83	0,83	0,83	0,83	0,83
Western Africa	0,31	0,31	0,31	0,31	0,31	0,31
Northern America	2,42	2,42	2,42	2,42	2,42	2,42
Central America	0,05	0,05	0,05	0,05	0,05	0,05
South America	0,19	0,19	0,19	0,19	0,19	0,19
Central Asia	1,57	1,57	1,57	1,57	1,57	1,57
Eastern Asia	2,37	2,37	2,37	2,37	2,37	2,37
Southern Asia	22,81	22,81	22,81	22,81	22,81	22,81
South-eastern Asia	3,63	3,63	3,63	3,63	3,63	3,63
Western Asia	1,16	1,16	1,16	1,16	1,16	1,16
Oceania	6,07	6,07	6,07	6,07	6,07	6,07
Eastern Europe	0,44	0,44	0,44	0,44	0,44	0,44
Northern Europe	3,79	3,79	3,79	3,79	3,79	3,79
Southern Europe	1,30	1,30	1,30	1,30	1,30	1,30
Western Europe	1,84	1,84	1,84	1,84	1,84	1,84

Table B.28: Projected availability of manure (HS scenario).

Unit: EJ	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Eastern Africa	0,43	0,49	0,57	0,66	0,77	0,89
Middle Africa	0,24	0,30	0,38	0,49	0,62	0,80
Northern Africa	1,39	1,53	1,69	1,87	2,06	2,28
Southern Africa	0,81	0,77	0,73	0,70	0,66	0,63
Western Africa	0,35	0,43	0,52	0,63	0,77	0,94
Northern America	2,57	2,84	3,13	3,46	3,82	4,21
Central America	0,06	0,06	0,07	0,07	0,08	0,09
South America	0,19	0,20	0,21	0,23	0,24	0,25
Central Asia	1,72	1,99	2,31	2,68	3,10	3,60
Eastern Asia	2,44	2,56	2,69	2,83	2,97	3,13
Southern Asia	23,50	24,70	25,96	27,28	28,67	30,14
South-eastern Asia	3,97	4,60	5,33	6,18	7,17	8,31
Western Asia	1,27	1,47	1,71	1,98	2,29	2,66
Oceania	6,07	6,07	6,07	6,07	6,07	6,07
Eastern Europe	0,45	0,48	0,50	0,53	0,55	0,58
Northern Europe	3,90	4,10	4,31	4,53	4,76	5,00
Southern Europe	1,38	1,53	1,69	1,86	2,06	2,27
Western Europe	1,84	1,84	1,84	1,84	1,84	1,84

Table B.29

	Collected wasterwater (10E9 m^3/year)	Population share per region	Collected wasetwater per region (10E9m^3/year)	Percentage sludge (dry g/liter)	Collected wasetwater per region (ton/year)	Total sludge potential (EJ/year)
Eastern Africa		33%	3,47	0,20	6,89E+05	0,01
Middle Africa		13%	1,40	0,20	2,78E+05	0,00
Northern Africa	1,04E+01	18%	1,92	0,20	3,81E+05	0,00
Southern Africa		5%	0,53	0,20	1,04E+05	0,00
Western Africa		30%	3,13	0,20	6,21E+05	0,01
Northern America		38%	26,78	0,20	5,32E+06	0,06
Central America	7,11E+01	18%	13,05	0,20	2,59E+06	0,03
South America		44%	31,28	0,20	6,21E+06	0,07
Central Asia		2%	0,81	0,20	1,61E+05	0,00
Eastern Asia		37%	18,19	0,20	3,61E+06	0,04
Southern Asia	4,95E+01	40%	19,80	0,20	3,93E+06	0,05
South-eastern Asia		15%	7,30	0,20	1,45E+06	0,02
Western Asia		7%	3,42	0,20	6,79E+05	0,01
Oceania	1,58E+00	100%	1,58	0,20	3,14E+05	0,00
Eastern Europe		39%	14,89	0,20	2,96E+06	0,04
Northern Europe	3,80E+01	14%	5,40	0,20	1,07E+06	0,01
Southern Europe		20%	7,74	0,20	1,54E+06	0,02
Western Europe		26%	9,97	0,20	1,98E+06	0,02

Table B.30: Projected availability of sludge (LS scenario).

Unit: EJ	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Eastern Africa	0,04	0,05	0,06	0,06	0,07	0,08
Middle Africa	0,02	0,02	0,02	0,03	0,03	0,03
Northern Africa	0,02	0,03	0,03	0,04	0,04	0,05
Southern Africa	0,01	0,01	0,01	0,01	0,01	0,01
Western Africa	0,04	0,05	0,05	0,06	0,07	0,07
Northern America	0,33	0,34	0,35	0,36	0,37	0,38
Central America	0,16	0,17	0,17	0,18	0,19	0,20
South America	0,38	0,40	0,42	0,44	0,46	0,48
Central Asia	0,01	0,01	0,01	0,01	0,01	0,01
Eastern Asia	0,22	0,23	0,24	0,25	0,26	0,28
Southern Asia	0,24	0,25	0,26	0,28	0,29	0,30
South-eastern Asia	0,09	0,09	0,10	0,10	0,11	0,11
Western Asia	0,04	0,04	0,05	0,05	0,05	0,05
Oceania	0,02	0,02	0,02	0,02	0,03	0,03
Eastern Europe	0,18	0,18	0,18	0,18	0,18	0,18
Northern Europe	0,07	0,07	0,07	0,07	0,07	0,07
Southern Europe	0,09	0,09	0,09	0,09	0,09	0,09
Western Europe	0,12	0,12	0,13	0,13	0,13	0,13

Table B.31: Projected availability of sludge (HS scenario).

Unit: EJ	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Eastern Africa	0,05	0,05	0,06	0,07	0,08	0,09
Middle Africa	0,02	0,02	0,02	0,03	0,03	0,04
Northern Africa	0,02	0,03	0,03	0,04	0,05	0,05
Southern Africa	0,01	0,01	0,01	0,01	0,01	0,01
Western Africa	0,04	0,05	0,05	0,06	0,07	0,09
Northern America	0,33	0,35	0,36	0,38	0,40	0,42
Central America	0,16	0,17	0,18	0,19	0,20	0,21
South America	0,38	0,40	0,42	0,45	0,47	0,49
Central Asia	0,01	0,01	0,01	0,01	0,01	0,01
Eastern Asia	0,22	0,23	0,25	0,26	0,27	0,29
Southern Asia	0,24	0,26	0,27	0,28	0,30	0,31
South-eastern Asia	0,09	0,09	0,10	0,10	0,11	0,11
Western Asia	0,04	0,04	0,05	0,05	0,05	0,05
Oceania	0,02	0,02	0,02	0,02	0,03	0,03
Eastern Europe	0,18	0,18	0,18	0,18	0,19	0,19
Northern Europe	0,07	0,07	0,07	0,07	0,07	0,08
Southern Europe	0,09	0,09	0,09	0,09	0,09	0,09
Western Europe	0,12	0,12	0,13	0,13	0,13	0,14

B.2. Competing users

In this appendix, supporting information on the estimation of biomass use by competing users is provided.

B.2.1. Renewable heat and electricity

Renewable heat and electricity is assumed to take over part of the share of traditional biomass in the future. In the High Supply (HS) scenario, a more rapid replacement of traditional biomass is considered compared to the Low Supply (LS) scenario. Most data is acquired from the IEA.

Table B.32: Projected demand for biomass from renewable heat and electricity (LS scenario).

	Renewable heat and electricity demand (2020-2025)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Western Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Northern America	0,00	0,00	0,65	0,65	0,65	0,88	1,61
Central America	0,00	0,00	0,23	0,23	0,23	0,02	0,00
South America	0,00	0,00	0,87	0,87	0,87	0,08	0,00
Central Asia	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Eastern Asia	0,00	0,00	1,82	1,82	1,82	0,04	2,42
Southern Asia	0,00	0,00	1,39	1,39	1,39	0,11	0,16
South-eastern Asia	0,00	0,00	0,49	0,49	0,49	0,07	0,21
Western Asia	0,00	0,00	0,00	0,00	0,00	0,10	0,03
Oceania	0,00	0,00	0,05	0,05	0,05	0,09	0,00
Eastern Europe	0,00	0,00	0,30	0,30	0,30	0,21	0,93
Northern Europe	0,00	0,00	0,84	0,84	0,84	0,59	1,24
Southern Europe	0,00	0,00	0,22	0,22	0,22	0,52	0,55
Western Europe	0,00	0,00	0,47	0,47	0,47	1,54	2,92

Table B.33: Projected demand for biomass from renewable heat and electricity (LS scenario).

	Renewable heat and electricity demand (2025-2030)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Western Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Northern America	0,00	0,00	0,72	0,72	0,72	0,97	1,78
Central America	0,00	0,00	0,26	0,26	0,26	0,02	0,01
South America	0,00	0,00	0,96	0,96	0,96	0,09	0,00
Central Asia	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Eastern Asia	0,00	0,00	2,01	2,01	2,01	0,05	2,67
Southern Asia	0,00	0,00	1,53	1,53	1,53	0,12	0,18
South-eastern Asia	0,00	0,00	0,54	0,54	0,54	0,07	0,23
Western Asia	0,00	0,00	0,00	0,00	0,00	0,11	0,03
Oceania	0,00	0,00	0,06	0,06	0,06	0,10	0,00
Eastern Europe	0,00	0,00	0,33	0,33	0,33	0,23	1,03
Northern Europe	0,00	0,00	0,93	0,93	0,93	0,65	1,36
Southern Europe	0,00	0,00	0,24	0,24	0,24	0,57	0,61
Western Europe	0,00	0,00	0,51	0,51	0,51	1,70	3,23

Table B.34: Projected demand for biomass from renewable heat and electricity (LS scenario).

	Renewable heat and electricity demand (2030-2035)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Western Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Northern America	0,00	0,00	0,79	0,79	0,79	1,07	1,96
Central America	0,00	0,00	0,28	0,28	0,28	0,02	0,01
South America	0,00	0,00	1,06	1,06	1,06	0,10	0,00
Central Asia	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Eastern Asia	0,00	0,00	2,22	2,22	2,22	0,05	2,95
Southern Asia	0,00	0,00	1,69	1,69	1,69	0,13	0,19
South-eastern Asia	0,00	0,00	0,60	0,60	0,60	0,08	0,25
Western Asia	0,00	0,00	0,01	0,01	0,01	0,12	0,03
Oceania	0,00	0,00	0,06	0,06	0,06	0,11	0,00
Eastern Europe	0,00	0,00	0,36	0,36	0,36	0,25	1,14
Northern Europe	0,00	0,00	1,03	1,03	1,03	0,72	1,51
Southern Europe	0,00	0,00	0,27	0,27	0,27	0,63	0,67
Western Europe	0,00	0,00	0,57	0,57	0,57	1,87	3,57

Table B.35: Projected demand for biomass from renewable heat and electricity (LS scenario).

	Renewable heat and electricity demand (2035-2040)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,02	0,02	0,02	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Western Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Northern America	0,00	0,00	0,87	0,87	0,87	1,18	2,17
Central America	0,00	0,00	0,31	0,31	0,31	0,02	0,01
South America	0,00	0,00	1,17	1,17	1,17	0,11	0,00
Central Asia	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Eastern Asia	0,00	0,00	2,45	2,45	2,45	0,06	3,26
Southern Asia	0,00	0,00	1,86	1,86	1,86	0,14	0,21
South-eastern Asia	0,00	0,00	0,66	0,66	0,66	0,09	0,28
Western Asia	0,00	0,00	0,01	0,01	0,01	0,14	0,04
Oceania	0,00	0,00	0,07	0,07	0,07	0,12	0,00
Eastern Europe	0,00	0,00	0,40	0,40	0,40	0,28	1,25
Northern Europe	0,00	0,00	1,13	1,13	1,13	0,80	1,66
Southern Europe	0,00	0,00	0,29	0,29	0,29	0,69	0,74
Western Europe	0,00	0,00	0,63	0,63	0,63	2,07	3,94

Table B.36: Projected demand for biomass from renewable heat and electricity (LS scenario).

	Renewable heat and electricity demand (2040-2045)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,02	0,02	0,02	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Western Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Northern America	0,00	0,00	0,97	0,97	0,97	1,30	2,39
Central America	0,00	0,00	0,34	0,34	0,34	0,02	0,01
South America	0,00	0,00	1,29	1,29	1,29	0,12	0,00
Central Asia	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Eastern Asia	0,00	0,00	2,71	2,71	2,71	0,07	3,60
Southern Asia	0,00	0,00	2,06	2,06	2,06	0,16	0,24
South-eastern Asia	0,00	0,00	0,73	0,73	0,73	0,10	0,31
Western Asia	0,00	0,00	0,01	0,01	0,01	0,15	0,04
Oceania	0,00	0,00	0,08	0,08	0,08	0,13	0,00
Eastern Europe	0,00	0,00	0,44	0,44	0,44	0,31	1,38
Northern Europe	0,00	0,00	1,25	1,25	1,25	0,88	1,84
Southern Europe	0,00	0,00	0,32	0,32	0,32	0,77	0,82
Western Europe	0,00	0,00	0,69	0,69	0,69	2,28	4,35

Table B.37: Projected demand for biomass from renewable heat and electricity (LS scenario).

	Renewable heat and electricity demand (2045-2050)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,02	0,02	0,02	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Western Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Northern America	0,00	0,00	1,07	1,07	1,07	1,44	2,64
Central America	0,00	0,00	0,38	0,38	0,38	0,03	0,01
South America	0,00	0,00	1,42	1,42	1,42	0,13	0,00
Central Asia	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Eastern Asia	0,00	0,00	2,99	2,99	2,99	0,07	3,97
Southern Asia	0,00	0,00	2,27	2,27	2,27	0,17	0,26
South-eastern Asia	0,00	0,00	0,80	0,80	0,80	0,11	0,34
Western Asia	0,00	0,00	0,01	0,01	0,01	0,16	0,05
Oceania	0,00	0,00	0,08	0,08	0,08	0,15	0,00
Eastern Europe	0,00	0,00	0,49	0,49	0,49	0,34	1,53
Northern Europe	0,00	0,00	1,38	1,38	1,38	0,97	2,03
Southern Europe	0,00	0,00	0,36	0,36	0,36	0,85	0,90
Western Europe	0,00	0,00	0,76	0,76	0,76	2,52	4,80

Table B.38: Projected demand for biomass from renewable heat and electricity (HS scenario).

	Renewable heat and electricity demand demand (2020-2025)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Western Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Northern America	0,00	0,00	0,69	0,69	0,69	0,93	1,71
Central America	0,00	0,00	0,25	0,25	0,25	0,02	0,01
South America	0,00	0,00	0,92	0,92	0,92	0,09	0,00
Central Asia	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Eastern Asia	0,00	0,00	1,93	1,93	1,93	0,05	2,57
Southern Asia	0,00	0,00	1,47	1,47	1,47	0,11	0,17
South-eastern Asia	0,00	0,00	0,52	0,52	0,52	0,07	0,22
Western Asia	0,00	0,00	0,00	0,00	0,00	0,11	0,03
Oceania	0,00	0,00	0,05	0,05	0,05	0,09	0,00
Eastern Europe	0,00	0,00	0,31	0,31	0,31	0,22	0,99
Northern Europe	0,00	0,00	0,89	0,89	0,89	0,63	1,31
Southern Europe	0,00	0,00	0,23	0,23	0,23	0,55	0,58
Western Europe	0,00	0,00	0,49	0,49	0,49	1,63	3,10

Table B.39: Projected demand for biomass from renewable heat and electricity (HS scenario).

	Renewable heat and electricity demand demand (2025-2030)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Western Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Northern America	0,00	0,00	0,84	0,84	0,84	1,13	2,08
Central America	0,00	0,00	0,30	0,30	0,30	0,02	0,01
South America	0,00	0,00	1,12	1,12	1,12	0,10	0,00
Central Asia	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Eastern Asia	0,00	0,00	2,35	2,35	2,35	0,06	3,12
Southern Asia	0,00	0,00	1,79	1,79	1,79	0,14	0,21
South-eastern Asia	0,00	0,00	0,63	0,63	0,63	0,09	0,27
Western Asia	0,00	0,00	0,01	0,01	0,01	0,13	0,04
Oceania	0,00	0,00	0,07	0,07	0,07	0,11	0,00
Eastern Europe	0,00	0,00	0,38	0,38	0,38	0,27	1,20
Northern Europe	0,00	0,00	1,09	1,09	1,09	0,77	1,60
Southern Europe	0,00	0,00	0,28	0,28	0,28	0,67	0,71
Western Europe	0,00	0,00	0,60	0,60	0,60	1,99	3,78

Table B.40: Projected demand for biomass from renewable heat and electricity (HS scenario).

	Renewable heat and electricity demand demand (2030-2035)						
	Vegetable oils	Waste oils	Forestry residues	Agricultural residues	Energy crops	Liquid waste	Solid waste
Eastern Africa	0,00	0,00	0,02	0,02	0,02	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Western Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Northern America	0,00	0,00	1,02	1,02	1,02	1,38	2,53
Central America	0,00	0,00	0,36	0,36	0,36	0,03	0,01
South America	0,00	0,00	1,36	1,36	1,36	0,13	0,00
Central Asia	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Eastern Asia	0,00	0,00	2,86	2,86	2,86	0,07	3,80
Southern Asia	0,00	0,00	2,18	2,18	2,18	0,17	0,25
South-eastern Asia	0,00	0,00	0,77	0,77	0,77	0,11	0,33
Western Asia	0,00	0,00	0,01	0,01	0,01	0,16	0,04
Oceania	0,00	0,00	0,08	0,08	0,08	0,14	0,00
Eastern Europe	0,00	0,00	0,47	0,47	0,47	0,33	1,46
Northern Europe	0,00	0,00	1,32	1,32	1,32	0,93	1,94
Southern Europe	0,00	0,00	0,34	0,34	0,34	0,81	0,87
Western Europe	0,00	0,00	0,73	0,73	0,73	2,42	4,59

Table B.41: Projected demand for biomass from renewable heat and electricity (HS scenario).

	Renewable heat and electricity demand demand (2035-2040)						
	Vegetable oils	Waste oils	Forestry residues	Agricultural residues	Energy crops	Liquid waste	Solid waste
Eastern Africa	0,00	0,00	0,02	0,02	0,02	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Western Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Northern America	0,00	0,00	1,24	1,24	1,24	1,68	3,07
Central America	0,00	0,00	0,44	0,44	0,44	0,03	0,01
South America	0,00	0,00	1,66	1,66	1,66	0,15	0,00
Central Asia	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Eastern Asia	0,00	0,00	3,48	3,48	3,48	0,08	4,63
Southern Asia	0,00	0,00	2,65	2,65	2,65	0,20	0,30
South-eastern Asia	0,00	0,00	0,94	0,94	0,94	0,13	0,40
Western Asia	0,00	0,00	0,01	0,01	0,01	0,19	0,05
Oceania	0,00	0,00	0,10	0,10	0,10	0,17	0,00
Eastern Europe	0,00	0,00	0,57	0,57	0,57	0,40	1,78
Northern Europe	0,00	0,00	1,61	1,61	1,61	1,13	2,36
Southern Europe	0,00	0,00	0,42	0,42	0,42	0,99	1,05
Western Europe	0,00	0,00	0,89	0,89	0,89	2,94	5,59

Table B.42: Projected demand for biomass from renewable heat and electricity (HS scenario).

	Renewable heat and electricity demand demand (2040-2045)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,03	0,03	0,03	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Western Africa	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Northern America	0,00	0,00	1,51	1,51	1,51	2,04	3,74
Central America	0,00	0,00	0,54	0,54	0,54	0,04	0,01
South America	0,00	0,00	2,02	2,02	2,02	0,19	0,00
Central Asia	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Eastern Asia	0,00	0,00	4,24	4,24	4,24	0,10	5,63
Southern Asia	0,00	0,00	3,22	3,22	3,22	0,25	0,37
South-eastern Asia	0,00	0,00	1,14	1,14	1,14	0,16	0,48
Western Asia	0,00	0,00	0,01	0,01	0,01	0,23	0,06
Oceania	0,00	0,00	0,12	0,12	0,12	0,21	0,00
Eastern Europe	0,00	0,00	0,69	0,69	0,69	0,48	2,17
Northern Europe	0,00	0,00	1,96	1,96	1,96	1,38	2,87
Southern Europe	0,00	0,00	0,51	0,51	0,51	1,20	1,28
Western Europe	0,00	0,00	1,08	1,08	1,08	3,58	6,80

Table B.43: Projected demand for biomass from renewable heat and electricity (HS scenario).

	Renewable heat and electricity demand (2045-2050)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,03	0,03	0,03	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,02	0,02	0,02	0,00	0,00
Western Africa	0,00	0,00	0,02	0,02	0,02	0,00	0,00
Northern America	0,00	0,00	1,84	1,84	1,84	2,48	4,55
Central America	0,00	0,00	0,66	0,66	0,66	0,05	0,01
South America	0,00	0,00	2,46	2,46	2,46	0,23	0,00
Central Asia	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Eastern Asia	0,00	0,00	5,16	5,16	5,16	0,12	6,85
Southern Asia	0,00	0,00	3,92	3,92	3,92	0,30	0,45
South-eastern Asia	0,00	0,00	1,39	1,39	1,39	0,19	0,59
Western Asia	0,00	0,00	0,01	0,01	0,01	0,28	0,08
Oceania	0,00	0,00	0,14	0,14	0,14	0,25	0,00
Eastern Europe	0,00	0,00	0,84	0,84	0,84	0,59	2,64
Northern Europe	0,00	0,00	2,38	2,38	2,38	1,68	3,50
Southern Europe	0,00	0,00	0,62	0,62	0,62	1,46	1,56
Western Europe	0,00	0,00	1,32	1,32	1,32	4,35	8,27

B.2.2. Traditional heat

Traditional heats is responsible for the most significant part of biomass use to date. In the Low Supply (LS) scenario, a graduate replacement of this type of energy use by renewable heat is assumed. In the High Supply (HS) scenario, a rapid replacement of traditional biomass use by renewable heat is assumed.

Table B.44: Projected demand for biomass from traditional heat (LS scenario).

	Traditional heat (2025-2030)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	6,59	3,29	0,00	0,00	1,10
Middle Africa	0,00	0,00	6,59	3,29	0,00	0,00	1,10
Northern Africa	0,00	0,00	6,59	3,29	0,00	0,00	1,10
Southern Africa	0,00	0,00	6,59	3,29	0,00	0,00	1,10
Western Africa	0,00	0,00	6,59	3,29	0,00	0,00	1,10
Northern America	0,00	0,00	6,05	3,02	0,00	0,00	1,01
Central America	0,00	0,00	3,02	1,51	0,00	0,00	0,50
South America	0,00	0,00	6,05	3,02	0,00	0,00	1,01
Central Asia	0,00	0,00	8,78	4,39	0,00	0,00	1,46
Eastern Asia	0,00	0,00	13,18	6,59	0,00	0,00	2,20
Southern Asia	0,00	0,00	13,18	6,59	0,00	0,00	2,20
South-eastern Asia	0,00	0,00	6,59	3,29	0,00	0,00	1,10
Western Asia	0,00	0,00	2,20	1,10	0,00	0,00	0,37
Oceania	0,00	0,00	0,54	0,27	0,00	0,00	0,09
Eastern Europe	0,00	0,00	3,82	1,91	0,00	0,00	0,64
Northern Europe	0,00	0,00	2,39	1,19	0,00	0,00	0,40
Southern Europe	0,00	0,00	1,43	0,72	0,00	0,00	0,24
Western Europe	0,00	0,00	0,10	0,05	0,00	0,00	0,02

Table B.45: Projected demand for biomass from traditional heat (LS scenario).

	Traditional heat (2030-2035)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	5,95	2,98	0,00	0,00	0,99
Middle Africa	0,00	0,00	5,95	2,98	0,00	0,00	0,99
Northern Africa	0,00	0,00	5,95	2,98	0,00	0,00	0,99
Southern Africa	0,00	0,00	5,95	2,98	0,00	0,00	0,99
Western Africa	0,00	0,00	5,95	2,98	0,00	0,00	0,99
Northern America	0,00	0,00	5,47	2,73	0,00	0,00	0,91
Central America	0,00	0,00	2,73	1,37	0,00	0,00	0,46
South America	0,00	0,00	5,47	2,73	0,00	0,00	0,91
Central Asia	0,00	0,00	7,94	3,97	0,00	0,00	1,32
Eastern Asia	0,00	0,00	11,91	5,95	0,00	0,00	1,98
Southern Asia	0,00	0,00	11,91	5,95	0,00	0,00	1,98
South-eastern Asia	0,00	0,00	5,95	2,98	0,00	0,00	0,99
Western Asia	0,00	0,00	1,98	0,99	0,00	0,00	0,33
Oceania	0,00	0,00	0,48	0,24	0,00	0,00	0,08
Eastern Europe	0,00	0,00	3,45	1,73	0,00	0,00	0,58
Northern Europe	0,00	0,00	2,16	1,08	0,00	0,00	0,36
Southern Europe	0,00	0,00	1,29	0,65	0,00	0,00	0,22
Western Europe	0,00	0,00	0,09	0,04	0,00	0,00	0,01

Table B.46: Projected demand for biomass from traditional heat (LS scenario).

	Traditional heat (2035-2040)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	5,38	2,69	0,00	0,00	0,90
Middle Africa	0,00	0,00	5,38	2,69	0,00	0,00	0,90
Northern Africa	0,00	0,00	5,38	2,69	0,00	0,00	0,90
Southern Africa	0,00	0,00	5,38	2,69	0,00	0,00	0,90
Western Africa	0,00	0,00	5,38	2,69	0,00	0,00	0,90
Northern America	0,00	0,00	4,94	2,47	0,00	0,00	0,82
Central America	0,00	0,00	2,47	1,24	0,00	0,00	0,41
South America	0,00	0,00	4,94	2,47	0,00	0,00	0,82
Central Asia	0,00	0,00	7,18	3,59	0,00	0,00	1,20
Eastern Asia	0,00	0,00	10,77	5,38	0,00	0,00	1,79
Southern Asia	0,00	0,00	10,77	5,38	0,00	0,00	1,79
South-eastern Asia	0,00	0,00	5,38	2,69	0,00	0,00	0,90
Western Asia	0,00	0,00	1,79	0,90	0,00	0,00	0,30
Oceania	0,00	0,00	0,44	0,22	0,00	0,00	0,07
Eastern Europe	0,00	0,00	3,12	1,56	0,00	0,00	0,52
Northern Europe	0,00	0,00	1,95	0,98	0,00	0,00	0,33
Southern Europe	0,00	0,00	1,17	0,59	0,00	0,00	0,20
Western Europe	0,00	0,00	0,08	0,04	0,00	0,00	0,01

Table B.47: Projected demand for biomass from traditional heat (LS scenario).

	Traditional heat (2040-2045)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	4,87	2,43	0,00	0,00	0,81
Middle Africa	0,00	0,00	4,87	2,43	0,00	0,00	0,81
Northern Africa	0,00	0,00	4,87	2,43	0,00	0,00	0,81
Southern Africa	0,00	0,00	4,87	2,43	0,00	0,00	0,81
Western Africa	0,00	0,00	4,87	2,43	0,00	0,00	0,81
Northern America	0,00	0,00	4,47	2,23	0,00	0,00	0,74
Central America	0,00	0,00	2,23	1,12	0,00	0,00	0,37
South America	0,00	0,00	4,47	2,23	0,00	0,00	0,74
Central Asia	0,00	0,00	6,49	3,24	0,00	0,00	1,08
Eastern Asia	0,00	0,00	9,73	4,87	0,00	0,00	1,62
Southern Asia	0,00	0,00	9,73	4,87	0,00	0,00	1,62
South-eastern Asia	0,00	0,00	4,87	2,43	0,00	0,00	0,81
Western Asia	0,00	0,00	1,62	0,81	0,00	0,00	0,27
Oceania	0,00	0,00	0,40	0,20	0,00	0,00	0,07
Eastern Europe	0,00	0,00	2,82	1,41	0,00	0,00	0,47
Northern Europe	0,00	0,00	1,76	0,88	0,00	0,00	0,29
Southern Europe	0,00	0,00	1,06	0,53	0,00	0,00	0,18
Western Europe	0,00	0,00	0,07	0,04	0,00	0,00	0,01

Table B.48: Projected demand for biomass from traditional heat (LS scenario).

	Traditional heat (2045-2050)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	4,40	2,20	0,00	0,00	0,73
Middle Africa	0,00	0,00	4,40	2,20	0,00	0,00	0,73
Northern Africa	0,00	0,00	4,40	2,20	0,00	0,00	0,73
Southern Africa	0,00	0,00	4,40	2,20	0,00	0,00	0,73
Western Africa	0,00	0,00	4,40	2,20	0,00	0,00	0,73
Northern America	0,00	0,00	4,04	2,02	0,00	0,00	0,67
Central America	0,00	0,00	2,02	1,01	0,00	0,00	0,34
South America	0,00	0,00	4,04	2,02	0,00	0,00	0,67
Central Asia	0,00	0,00	5,86	2,93	0,00	0,00	0,98
Eastern Asia	0,00	0,00	8,80	4,40	0,00	0,00	1,47
Southern Asia	0,00	0,00	8,80	4,40	0,00	0,00	1,47
South-eastern Asia	0,00	0,00	4,40	2,20	0,00	0,00	0,73
Western Asia	0,00	0,00	1,47	0,73	0,00	0,00	0,24
Oceania	0,00	0,00	0,36	0,18	0,00	0,00	0,06
Eastern Europe	0,00	0,00	2,55	1,28	0,00	0,00	0,43
Northern Europe	0,00	0,00	1,59	0,80	0,00	0,00	0,27
Southern Europe	0,00	0,00	0,96	0,48	0,00	0,00	0,16
Western Europe	0,00	0,00	0,06	0,03	0,00	0,00	0,01

Table B.49: Projected demand for biomass from traditional heat (HS scenario).

	Traditional heat (2020-2025)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	6,84	3,42	0,00	0,00	1,14
Middle Africa	0,00	0,00	6,84	3,42	0,00	0,00	1,14
Northern Africa	0,00	0,00	6,84	3,42	0,00	0,00	1,14
Southern Africa	0,00	0,00	6,84	3,42	0,00	0,00	1,14
Western Africa	0,00	0,00	6,84	3,42	0,00	0,00	1,14
Northern America	0,00	0,00	6,28	3,14	0,00	0,00	1,05
Central America	0,00	0,00	3,14	1,57	0,00	0,00	0,52
South America	0,00	0,00	6,28	3,14	0,00	0,00	1,05
Central Asia	0,00	0,00	9,12	4,56	0,00	0,00	1,52
Eastern Asia	0,00	0,00	13,68	6,84	0,00	0,00	2,28
Southern Asia	0,00	0,00	13,68	6,84	0,00	0,00	2,28
South-eastern Asia	0,00	0,00	6,84	3,42	0,00	0,00	1,14
Western Asia	0,00	0,00	2,28	1,14	0,00	0,00	0,38
Oceania	0,00	0,00	0,56	0,28	0,00	0,00	0,09
Eastern Europe	0,00	0,00	3,97	1,98	0,00	0,00	0,66
Northern Europe	0,00	0,00	2,48	1,24	0,00	0,00	0,41
Southern Europe	0,00	0,00	1,49	0,74	0,00	0,00	0,25
Western Europe	0,00	0,00	0,10	0,05	0,00	0,00	0,02

Table B.50: Projected demand for biomass from traditional heat (HS scenario).

	Traditional heat (2035-2030)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	5,55	2,77	0,00	0,00	0,92
Middle Africa	0,00	0,00	5,55	2,77	0,00	0,00	0,92
Northern Africa	0,00	0,00	5,55	2,77	0,00	0,00	0,92
Southern Africa	0,00	0,00	5,55	2,77	0,00	0,00	0,92
Western Africa	0,00	0,00	5,55	2,77	0,00	0,00	0,92
Northern America	0,00	0,00	5,09	2,55	0,00	0,00	0,85
Central America	0,00	0,00	2,55	1,27	0,00	0,00	0,42
South America	0,00	0,00	5,09	2,55	0,00	0,00	0,85
Central Asia	0,00	0,00	7,40	3,70	0,00	0,00	1,23
Eastern Asia	0,00	0,00	11,09	5,55	0,00	0,00	1,85
Southern Asia	0,00	0,00	11,09	5,55	0,00	0,00	1,85
South-eastern Asia	0,00	0,00	5,55	2,77	0,00	0,00	0,92
Western Asia	0,00	0,00	1,85	0,92	0,00	0,00	0,31
Oceania	0,00	0,00	0,45	0,23	0,00	0,00	0,08
Eastern Europe	0,00	0,00	3,22	1,61	0,00	0,00	0,54
Northern Europe	0,00	0,00	2,01	1,01	0,00	0,00	0,34
Southern Europe	0,00	0,00	1,21	0,60	0,00	0,00	0,20
Western Europe	0,00	0,00	0,08	0,04	0,00	0,00	0,01

Table B.51: Projected demand for biomass from traditional heat (HS scenario).

	Traditional heat (2030-2035)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	4,50	2,25	0,00	0,00	0,75
Middle Africa	0,00	0,00	4,50	2,25	0,00	0,00	0,75
Northern Africa	0,00	0,00	4,50	2,25	0,00	0,00	0,75
Southern Africa	0,00	0,00	4,50	2,25	0,00	0,00	0,75
Western Africa	0,00	0,00	4,50	2,25	0,00	0,00	0,75
Northern America	0,00	0,00	4,13	2,06	0,00	0,00	0,69
Central America	0,00	0,00	2,06	1,03	0,00	0,00	0,34
South America	0,00	0,00	4,13	2,06	0,00	0,00	0,69
Central Asia	0,00	0,00	6,00	3,00	0,00	0,00	1,00
Eastern Asia	0,00	0,00	9,00	4,50	0,00	0,00	1,50
Southern Asia	0,00	0,00	9,00	4,50	0,00	0,00	1,50
South-eastern Asia	0,00	0,00	4,50	2,25	0,00	0,00	0,75
Western Asia	0,00	0,00	1,50	0,75	0,00	0,00	0,25
Oceania	0,00	0,00	0,37	0,18	0,00	0,00	0,06
Eastern Europe	0,00	0,00	2,61	1,30	0,00	0,00	0,43
Northern Europe	0,00	0,00	1,63	0,82	0,00	0,00	0,27
Southern Europe	0,00	0,00	0,98	0,49	0,00	0,00	0,16
Western Europe	0,00	0,00	0,07	0,03	0,00	0,00	0,01

Table B.52: Projected demand for biomass from traditional heat (HS scenario).

	Traditional heat (2035-2040)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	3,65	1,82	0,00	0,00	0,61
Middle Africa	0,00	0,00	3,65	1,82	0,00	0,00	0,61
Northern Africa	0,00	0,00	3,65	1,82	0,00	0,00	0,61
Southern Africa	0,00	0,00	3,65	1,82	0,00	0,00	0,61
Western Africa	0,00	0,00	3,65	1,82	0,00	0,00	0,61
Northern America	0,00	0,00	3,35	1,67	0,00	0,00	0,56
Central America	0,00	0,00	1,67	0,84	0,00	0,00	0,28
South America	0,00	0,00	3,35	1,67	0,00	0,00	0,56
Central Asia	0,00	0,00	4,87	2,43	0,00	0,00	0,81
Eastern Asia	0,00	0,00	7,30	3,65	0,00	0,00	1,22
Southern Asia	0,00	0,00	7,30	3,65	0,00	0,00	1,22
South-eastern Asia	0,00	0,00	3,65	1,82	0,00	0,00	0,61
Western Asia	0,00	0,00	1,22	0,61	0,00	0,00	0,20
Oceania	0,00	0,00	0,30	0,15	0,00	0,00	0,05
Eastern Europe	0,00	0,00	2,12	1,06	0,00	0,00	0,35
Northern Europe	0,00	0,00	1,32	0,66	0,00	0,00	0,22
Southern Europe	0,00	0,00	0,79	0,40	0,00	0,00	0,13
Western Europe	0,00	0,00	0,05	0,03	0,00	0,00	0,01

Table B.53: Projected demand for biomass from traditional heat (HS scenario).

	Traditional heat (2040-2045)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	2,96	1,48	0,00	0,00	0,49
Middle Africa	0,00	0,00	2,96	1,48	0,00	0,00	0,49
Northern Africa	0,00	0,00	2,96	1,48	0,00	0,00	0,49
Southern Africa	0,00	0,00	2,96	1,48	0,00	0,00	0,49
Western Africa	0,00	0,00	2,96	1,48	0,00	0,00	0,49
Northern America	0,00	0,00	2,72	1,36	0,00	0,00	0,45
Central America	0,00	0,00	1,36	0,68	0,00	0,00	0,23
South America	0,00	0,00	2,72	1,36	0,00	0,00	0,45
Central Asia	0,00	0,00	3,95	1,97	0,00	0,00	0,66
Eastern Asia	0,00	0,00	5,92	2,96	0,00	0,00	0,99
Southern Asia	0,00	0,00	5,92	2,96	0,00	0,00	0,99
South-eastern Asia	0,00	0,00	2,96	1,48	0,00	0,00	0,49
Western Asia	0,00	0,00	0,99	0,49	0,00	0,00	0,16
Oceania	0,00	0,00	0,24	0,12	0,00	0,00	0,04
Eastern Europe	0,00	0,00	1,72	0,86	0,00	0,00	0,29
Northern Europe	0,00	0,00	1,07	0,54	0,00	0,00	0,18
Southern Europe	0,00	0,00	0,64	0,32	0,00	0,00	0,11
Western Europe	0,00	0,00	0,04	0,02	0,00	0,00	0,01

Table B.54: Projected demand for biomass from traditional heat (HS scenario).

	Traditional heat (2045-2050)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	2,40	1,20	0,00	0,00	0,40
Middle Africa	0,00	0,00	2,40	1,20	0,00	0,00	0,40
Northern Africa	0,00	0,00	2,40	1,20	0,00	0,00	0,40
Southern Africa	0,00	0,00	2,40	1,20	0,00	0,00	0,40
Western Africa	0,00	0,00	2,40	1,20	0,00	0,00	0,40
Northern America	0,00	0,00	2,20	1,10	0,00	0,00	0,37
Central America	0,00	0,00	1,10	0,55	0,00	0,00	0,18
South America	0,00	0,00	2,20	1,10	0,00	0,00	0,37
Central Asia	0,00	0,00	3,20	1,60	0,00	0,00	0,53
Eastern Asia	0,00	0,00	4,80	2,40	0,00	0,00	0,80
Southern Asia	0,00	0,00	4,80	2,40	0,00	0,00	0,80
South-eastern Asia	0,00	0,00	2,40	1,20	0,00	0,00	0,40
Western Asia	0,00	0,00	0,80	0,40	0,00	0,00	0,13
Oceania	0,00	0,00	0,20	0,10	0,00	0,00	0,03
Eastern Europe	0,00	0,00	1,39	0,70	0,00	0,00	0,23
Northern Europe	0,00	0,00	0,87	0,44	0,00	0,00	0,15
Southern Europe	0,00	0,00	0,52	0,26	0,00	0,00	0,09
Western Europe	0,00	0,00	0,03	0,02	0,00	0,00	0,01

B.2.3. Road, rail and aviation

For the road sector, biodiesel consumption data of the EIA is used. To estimate the future biofuel use of the aviation industry, the outlook of the IEA is used. In the Low Supply (LS) scenario, demand from the road and aviation sector are expected to rise at a fast pace. For the High Supply (HS) scenario, biofuel demand from these sectors are expected to grow at a somewhat more modest pace.

Table B.55: Projected demand for biomass from road, rail and aviation (LS scenario).

	Distributed transport demand (2020-2025)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Western Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern America	1,23	0,37	0,31	0,31	0,31	0,00	0,00
Central America	0,19	0,01	0,01	0,01	0,01	0,00	0,00
South America	1,60	0,08	0,01	0,01	0,01	0,00	0,00
Central Asia	0,00	0,00	0,02	0,02	0,02	0,00	0,00
Eastern Asia	0,38	0,00	0,06	0,06	0,06	0,00	0,00
Southern Asia	0,04	0,00	0,01	0,01	0,01	0,00	0,00
South-eastern Asia	1,39	0,00	0,02	0,02	0,02	0,00	0,00
Western Asia	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Oceania	0,00	0,00	0,01	0,01	0,01	0,00	0,00
Eastern Europe	0,48	0,20	0,08	0,08	0,08	0,00	0,00
Northern Europe	0,36	0,15	0,02	0,02	0,02	0,00	0,00
Southern Europe	0,47	0,20	0,03	0,03	0,03	0,00	0,00
Western Europe	0,99	0,43	0,03	0,03	0,03	0,00	0,00

Table B.56: Projected demand for biomass from road, rail and aviation (LS scenario).

	Distributed transport demand (2025-2030)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Western Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern America	2,13	0,74	0,94	0,94	0,94	0,00	0,00
Central America	0,22	0,02	0,02	0,02	0,02	0,00	0,00
South America	1,80	0,10	0,03	0,03	0,03	0,00	0,00
Central Asia	0,05	0,02	0,06	0,06	0,06	0,00	0,00
Eastern Asia	0,57	0,07	0,19	0,19	0,19	0,00	0,00
Southern Asia	0,06	0,01	0,02	0,02	0,02	0,00	0,00
South-eastern Asia	1,58	0,02	0,06	0,06	0,06	0,00	0,00
Western Asia	0,03	0,01	0,03	0,03	0,03	0,00	0,00
Oceania	0,02	0,01	0,03	0,03	0,03	0,00	0,00
Eastern Europe	0,72	0,31	0,24	0,24	0,24	0,00	0,00
Northern Europe	0,46	0,20	0,07	0,07	0,07	0,00	0,00
Southern Europe	0,60	0,26	0,09	0,09	0,09	0,00	0,00
Western Europe	1,17	0,50	0,09	0,09	0,09	0,00	0,00

Table B.57: Projected demand for biomass from road, rail and aviation (LS scenario).

	Distributed transport demand (2030-2035)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Western Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern America	2,81	1,01	1,59	1,59	1,59	0,00	0,00
Central America	0,26	0,03	0,04	0,04	0,04	0,00	0,00
South America	2,00	0,12	0,05	0,05	0,05	0,00	0,00
Central Asia	0,08	0,03	0,10	0,10	0,10	0,00	0,00
Eastern Asia	0,72	0,11	0,32	0,32	0,32	0,00	0,00
Southern Asia	0,08	0,01	0,04	0,04	0,04	0,00	0,00
South-eastern Asia	1,77	0,03	0,10	0,10	0,10	0,00	0,00
Western Asia	0,05	0,02	0,06	0,06	0,06	0,00	0,00
Oceania	0,04	0,02	0,04	0,04	0,04	0,00	0,00
Eastern Europe	0,92	0,39	0,41	0,41	0,41	0,00	0,00
Northern Europe	0,54	0,23	0,12	0,12	0,12	0,00	0,00
Southern Europe	0,70	0,30	0,15	0,15	0,15	0,00	0,00
Western Europe	1,34	0,57	0,15	0,15	0,15	0,00	0,00

Table B.58: Projected demand for biomass from road, rail and aviation (LS scenario).

	Distributed transport demand (2035-2040)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Western Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern America	3,50	1,29	2,24	2,24	2,24	0,00	0,00
Central America	0,30	0,03	0,05	0,05	0,05	0,00	0,00
South America	2,22	0,14	0,08	0,08	0,08	0,00	0,00
Central Asia	0,11	0,05	0,13	0,13	0,13	0,00	0,00
Eastern Asia	0,88	0,16	0,45	0,45	0,45	0,00	0,00
Southern Asia	0,09	0,02	0,05	0,05	0,05	0,00	0,00
South-eastern Asia	1,98	0,05	0,13	0,13	0,13	0,00	0,00
Western Asia	0,07	0,03	0,08	0,08	0,08	0,00	0,00
Oceania	0,05	0,02	0,06	0,06	0,06	0,00	0,00
Eastern Europe	1,11	0,48	0,57	0,57	0,57	0,00	0,00
Northern Europe	0,63	0,27	0,17	0,17	0,17	0,00	0,00
Southern Europe	0,81	0,35	0,22	0,22	0,22	0,00	0,00
Western Europe	1,51	0,65	0,21	0,21	0,21	0,00	0,00

Table B.59: Projected demand for biomass from road, rail and aviation (LS scenario).

	Distributed transport demand (2040-2045)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Western Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern America	3,99	1,48	2,63	2,63	2,63	0,00	0,00
Central America	0,33	0,04	0,06	0,06	0,06	0,00	0,00
South America	2,46	0,16	0,09	0,09	0,09	0,00	0,00
Central Asia	0,13	0,06	0,16	0,16	0,16	0,00	0,00
Eastern Asia	1,00	0,19	0,53	0,53	0,53	0,00	0,00
Southern Asia	0,11	0,02	0,06	0,06	0,06	0,00	0,00
South-eastern Asia	2,20	0,06	0,16	0,16	0,16	0,00	0,00
Western Asia	0,08	0,03	0,09	0,09	0,09	0,00	0,00
Oceania	0,06	0,03	0,07	0,07	0,07	0,00	0,00
Eastern Europe	1,26	0,54	0,67	0,67	0,67	0,00	0,00
Northern Europe	0,71	0,30	0,21	0,21	0,21	0,00	0,00
Southern Europe	0,91	0,39	0,25	0,25	0,25	0,00	0,00
Western Europe	1,68	0,72	0,25	0,25	0,25	0,00	0,00

Table B.60: Projected demand for biomass from road, rail and aviation (LS scenario).

	Distributed transport demand (2045-2050)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Western Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern America	4,29	1,58	2,76	2,76	2,76	0,00	0,00
Central America	0,36	0,04	0,07	0,07	0,07	0,00	0,00
South America	2,71	0,17	0,09	0,09	0,09	0,00	0,00
Central Asia	0,14	0,06	0,17	0,17	0,17	0,00	0,00
Eastern Asia	1,08	0,20	0,55	0,55	0,55	0,00	0,00
Southern Asia	0,11	0,02	0,07	0,07	0,07	0,00	0,00
South-eastern Asia	2,42	0,06	0,17	0,17	0,17	0,00	0,00
Western Asia	0,08	0,04	0,10	0,10	0,10	0,00	0,00
Oceania	0,06	0,03	0,08	0,08	0,08	0,00	0,00
Eastern Europe	1,36	0,58	0,71	0,71	0,71	0,00	0,00
Northern Europe	0,77	0,33	0,22	0,22	0,22	0,00	0,00
Southern Europe	0,99	0,43	0,27	0,27	0,27	0,00	0,00
Western Europe	1,85	0,79	0,26	0,26	0,26	0,00	0,00

High Supply (HS) scenario

Table B.61: Projected demand for biomass from road, rail and aviation (HS scenario).

	Distributed transport demand (2020-2025)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Western Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern America	1,56	0,51	0,31	0,31	0,31	0,00	0,00
Central America	0,19	0,01	0,01	0,01	0,01	0,00	0,00
South America	1,57	0,09	0,01	0,01	0,01	0,00	0,00
Central Asia	0,02	0,01	0,02	0,02	0,02	0,00	0,00
Eastern Asia	0,44	0,03	0,06	0,06	0,06	0,00	0,00
Southern Asia	0,04	0,00	0,01	0,01	0,01	0,00	0,00
South-eastern Asia	1,37	0,01	0,02	0,02	0,02	0,00	0,00
Western Asia	0,01	0,01	0,01	0,01	0,01	0,00	0,00
Oceania	0,01	0,00	0,01	0,01	0,01	0,00	0,00
Eastern Europe	0,56	0,24	0,08	0,08	0,08	0,00	0,00
Northern Europe	0,38	0,16	0,02	0,02	0,02	0,00	0,00
Southern Europe	0,49	0,21	0,03	0,03	0,03	0,00	0,00
Western Europe	1,00	0,43	0,03	0,03	0,03	0,00	0,00

Table B.62: Projected demand for biomass from road, rail and aviation (HS scenario).

	Distributed transport demand (2025-2030)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Western Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern America	2,03	0,71	0,94	0,94	0,94	0,00	0,00
Central America	0,21	0,02	0,02	0,02	0,02	0,00	0,00
South America	1,66	0,10	0,03	0,03	0,03	0,00	0,00
Central Asia	0,05	0,02	0,06	0,06	0,06	0,00	0,00
Eastern Asia	0,54	0,07	0,19	0,19	0,19	0,00	0,00
Southern Asia	0,06	0,01	0,02	0,02	0,02	0,00	0,00
South-eastern Asia	1,46	0,02	0,06	0,06	0,06	0,00	0,00
Western Asia	0,03	0,01	0,03	0,03	0,03	0,00	0,00
Oceania	0,02	0,01	0,03	0,03	0,03	0,00	0,00
Eastern Europe	0,68	0,29	0,24	0,24	0,24	0,00	0,00
Northern Europe	0,43	0,18	0,07	0,07	0,07	0,00	0,00
Southern Europe	0,56	0,24	0,09	0,09	0,09	0,00	0,00
Western Europe	1,09	0,47	0,09	0,09	0,09	0,00	0,00

Table B.63: Projected demand for biomass from road, rail and aviation (HS scenario).

	Distributed transport demand (2030-2035)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Western Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern America	2,63	0,96	1,59	1,59	1,59	0,00	0,00
Central America	0,23	0,02	0,04	0,04	0,04	0,00	0,00
South America	1,76	0,11	0,05	0,05	0,05	0,00	0,00
Central Asia	0,08	0,03	0,10	0,10	0,10	0,00	0,00
Eastern Asia	0,67	0,11	0,32	0,32	0,32	0,00	0,00
Southern Asia	0,07	0,01	0,04	0,04	0,04	0,00	0,00
South-eastern Asia	1,57	0,03	0,10	0,10	0,10	0,00	0,00
Western Asia	0,05	0,02	0,06	0,06	0,06	0,00	0,00
Oceania	0,04	0,02	0,04	0,04	0,04	0,00	0,00
Eastern Europe	0,85	0,36	0,41	0,41	0,41	0,00	0,00
Northern Europe	0,49	0,21	0,12	0,12	0,12	0,00	0,00
Southern Europe	0,63	0,27	0,15	0,15	0,15	0,00	0,00
Western Europe	1,19	0,51	0,15	0,15	0,15	0,00	0,00

Table B.64: Projected demand for biomass from road, rail and aviation (HS scenario).

	Distributed transport demand (2035-2040)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Western Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern America	3,23	1,21	2,24	2,24	2,24	0,00	0,00
Central America	0,25	0,03	0,05	0,05	0,05	0,00	0,00
South America	1,87	0,12	0,08	0,08	0,08	0,00	0,00
Central Asia	0,11	0,05	0,13	0,13	0,13	0,00	0,00
Eastern Asia	0,80	0,16	0,45	0,45	0,45	0,00	0,00
Southern Asia	0,09	0,02	0,05	0,05	0,05	0,00	0,00
South-eastern Asia	1,68	0,05	0,13	0,13	0,13	0,00	0,00
Western Asia	0,07	0,03	0,08	0,08	0,08	0,00	0,00
Oceania	0,05	0,02	0,06	0,06	0,06	0,00	0,00
Eastern Europe	1,01	0,43	0,57	0,57	0,57	0,00	0,00
Northern Europe	0,55	0,24	0,17	0,17	0,17	0,00	0,00
Southern Europe	0,71	0,30	0,22	0,22	0,22	0,00	0,00
Western Europe	1,29	0,55	0,21	0,21	0,21	0,00	0,00

Table B.65: Projected demand for biomass from road, rail and aviation (HS scenario).

	Distributed transport demand (2040-2045)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Western Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern America	3,62	1,37	2,63	2,63	2,63	0,00	0,00
Central America	0,27	0,03	0,06	0,06	0,06	0,00	0,00
South America	1,97	0,13	0,09	0,09	0,09	0,00	0,00
Central Asia	0,13	0,06	0,16	0,16	0,16	0,00	0,00
Eastern Asia	0,88	0,19	0,53	0,53	0,53	0,00	0,00
Southern Asia	0,09	0,02	0,06	0,06	0,06	0,00	0,00
South-eastern Asia	1,78	0,06	0,16	0,16	0,16	0,00	0,00
Western Asia	0,08	0,03	0,09	0,09	0,09	0,00	0,00
Oceania	0,06	0,03	0,07	0,07	0,07	0,00	0,00
Eastern Europe	1,12	0,48	0,67	0,67	0,67	0,00	0,00
Northern Europe	0,60	0,26	0,21	0,21	0,21	0,00	0,00
Southern Europe	0,77	0,33	0,25	0,25	0,25	0,00	0,00
Western Europe	1,38	0,59	0,25	0,25	0,25	0,00	0,00

Table B.66: Projected demand for biomass from road, rail and aviation (HS scenario).

	Distributed transport demand (2045-2050)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Middle Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Southern Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Western Africa	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Northern America	3,80	1,43	2,76	2,76	2,76	0,00	0,00
Central America	0,29	0,04	0,07	0,07	0,07	0,00	0,00
South America	2,07	0,14	0,09	0,09	0,09	0,00	0,00
Central Asia	0,14	0,06	0,17	0,17	0,17	0,00	0,00
Eastern Asia	0,93	0,20	0,55	0,55	0,55	0,00	0,00
Southern Asia	0,10	0,02	0,07	0,07	0,07	0,00	0,00
South-eastern Asia	1,87	0,06	0,17	0,17	0,17	0,00	0,00
Western Asia	0,08	0,04	0,10	0,10	0,10	0,00	0,00
Oceania	0,06	0,03	0,08	0,08	0,08	0,00	0,00
Eastern Europe	1,18	0,50	0,71	0,71	0,71	0,00	0,00
Northern Europe	0,63	0,27	0,22	0,22	0,22	0,00	0,00
Southern Europe	0,81	0,35	0,27	0,27	0,27	0,00	0,00
Western Europe	1,45	0,62	0,26	0,26	0,26	0,00	0,00

B.3. Low Supply (LS) scenario

In the following tables, the estimated amount of biomass available for the maritime sector in the low biomass supply scenario is shown. It stands out that many values are negative, meaning that in that specific region the demand for biomass exceeds the domestic supply. This is especially the case for vegetable oils and waste oils. The main reason for this is the expectation that the use of vegetable oils for biofuel production will stagnate due to increasingly stringent sustainability requirements, while the demand from the transport section for oil crop based fuels will rise. Other values that become negative are forestry residues in Africa. This is caused by the assumption that a significant part of traditional biomass use consumes this feedstock. In reality, other types of fuel wood might be more dominantly used for this purpose. To be on the safe side, the forestry residue potential of Africa is assumed to be zero.

Table B.67: Projected biomass availability for the maritime industry (LS scenario).

	Available for marine (2020-2025)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	-0,07	2,79	5,97	0,43	-0,36
Middle Africa	0,00	0,00	-2,23	-0,26	0,46	0,22	-0,62
Northern Africa	0,00	0,00	-3,06	2,02	5,88	1,33	-0,35
Southern Africa	0,00	0,00	-3,32	-0,11	3,06	0,84	-0,95
Western Africa	0,00	0,00	-1,23	3,21	6,64	0,35	-0,21
Northern America	-0,67	0,03	54,02	21,24	10,10	1,87	0,59
Central America	-0,17	-0,01	0,13	1,54	2,44	0,20	-0,10
South America	-0,22	-0,06	5,09	19,07	37,76	0,49	0,47
Central Asia	0,03	0,00	-4,75	0,56	0,59	1,58	-1,47
Eastern Asia	0,27	1,00	1,21	33,72	0,00	2,54	0,01
Southern Asia	0,46	0,09	4,72	19,62	-0,62	22,94	0,20
South-eastern Asia	-0,02	0,03	3,72	14,03	0,11	3,65	0,21
Western Asia	0,05	0,02	-0,43	2,47	0,68	1,10	0,68
Oceania	0,00	0,00	9,49	3,29	9,40	6,00	0,62
Eastern Europe	1,44	-0,18	25,51	11,49	19,09	0,41	0,21
Northern Europe	-0,25	-0,12	11,23	0,51	0,72	3,26	-0,91
Southern Europe	-0,32	-0,16	4,21	2,47	1,16	0,88	0,59
Western Europe	-0,64	-0,35	11,12	4,11	0,69	0,43	-1,76

Table B.68: Projected biomass availability for the maritime industry (LS scenario).

	Available for marine (2025-2030)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	-0,81	3,41	6,73	0,44	-0,13
Middle Africa	0,00	0,00	-2,31	-0,02	0,51	0,22	-0,43
Northern Africa	0,00	0,00	-2,89	2,37	6,30	1,33	-0,12
Southern Africa	0,00	0,00	-3,07	0,14	3,45	0,84	-0,79
Western Africa	0,00	0,00	-1,62	3,89	7,47	0,36	0,03
Northern America	-1,53	-0,32	35,90	21,59	9,85	1,79	0,63
Central America	-0,20	-0,02	-0,37	1,76	2,64	0,20	-0,02
South America	-0,17	-0,08	2,47	20,92	41,05	0,50	0,65
Central Asia	-0,01	-0,02	-4,36	0,84	0,59	1,58	-1,30
Eastern Asia	0,12	0,99	-1,57	35,77	-0,22	2,55	0,21
Southern Asia	0,47	0,08	1,18	21,51	-0,72	22,94	0,54
South-eastern Asia	-0,12	0,01	1,59	15,28	0,06	3,65	0,37
Western Asia	0,02	0,01	-0,58	2,69	0,70	1,09	0,77
Oceania	-0,02	-0,01	6,50	3,41	9,76	6,00	0,68
Eastern Europe	1,58	-0,29	17,00	11,87	19,69	0,39	0,18
Northern Europe	-0,33	-0,16	7,14	0,49	0,65	3,20	-0,97
Southern Europe	-0,42	-0,21	2,60	2,53	1,14	0,83	0,55
Western Europe	-0,79	-0,42	7,46	4,19	0,63	0,27	-2,04

Table B.69: Projected biomass availability for the maritime industry (LS scenario).

	Available for marine (2030-2035)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	-0,88	4,01	7,46	0,45	0,11
Middle Africa	0,00	0,00	-2,14	0,20	0,57	0,23	-0,23
Northern Africa	0,00	0,00	-2,63	2,67	6,66	1,34	0,11
Southern Africa	0,00	0,00	-2,79	0,38	3,83	0,84	-0,65
Western Africa	0,00	0,00	-1,56	4,54	8,29	0,36	0,29
Northern America	-2,15	-0,56	29,27	21,57	9,42	1,70	0,65
Central America	-0,23	-0,03	-0,48	1,91	2,76	0,21	0,05
South America	-0,08	-0,10	1,65	22,17	43,28	0,51	0,82
Central Asia	-0,04	-0,03	-3,99	1,08	0,59	1,58	-1,16
Eastern Asia	0,01	1,00	-2,37	36,90	-0,49	2,55	0,36
Southern Asia	0,49	0,08	0,22	23,01	-0,85	22,94	0,86
South-eastern Asia	-0,22	0,00	0,97	16,27	0,01	3,64	0,53
Western Asia	0,01	0,00	-0,58	2,86	0,72	1,08	0,85
Oceania	-0,04	-0,01	5,46	3,49	9,98	5,99	0,74
Eastern Europe	1,84	-0,37	14,01	12,06	20,00	0,36	0,14
Northern Europe	-0,40	-0,20	5,68	0,43	0,54	3,13	-1,06
Southern Europe	-0,51	-0,25	2,03	2,55	1,09	0,77	0,50
Western Europe	-0,92	-0,49	6,12	4,20	0,54	0,09	-2,35

Table B.70: Projected biomass availability for the maritime industry (LS scenario).

	Available for marine (2035-2040)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	-0,65	4,60	8,20	0,45	0,35
Middle Africa	0,00	0,00	-1,88	0,41	0,63	0,23	-0,04
Northern Africa	0,00	0,00	-2,36	2,93	6,96	1,34	0,35
Southern Africa	0,00	0,00	-2,51	0,62	4,20	0,84	-0,51
Western Africa	0,00	0,00	-1,31	5,18	9,10	0,37	0,55
Northern America	-2,78	-0,82	27,95	21,30	8,86	1,59	0,64
Central America	-0,27	-0,03	-0,42	2,01	2,83	0,21	0,11
South America	0,03	-0,12	1,64	22,99	44,72	0,52	0,99
Central Asia	-0,07	-0,05	-3,65	1,29	0,59	1,58	-1,02
Eastern Asia	-0,09	1,02	-2,31	37,35	-0,82	2,56	0,48
Southern Asia	0,51	0,08	0,40	24,23	-1,00	22,94	1,16
South-eastern Asia	-0,32	-0,01	1,04	17,09	-0,06	3,64	0,68
Western Asia	-0,01	0,00	-0,52	3,00	0,73	1,07	0,93
Oceania	-0,05	-0,02	5,31	3,52	10,11	5,98	0,80
Eastern Europe	2,19	-0,45	13,57	12,11	20,11	0,34	0,07
Northern Europe	-0,48	-0,23	5,43	0,33	0,41	3,06	-1,16
Southern Europe	-0,61	-0,30	1,92	2,53	1,02	0,70	0,44
Western Europe	-1,05	-0,56	5,83	4,15	0,44	-0,10	-2,70

Table B.71: Projected biomass availability for the maritime industry (LS scenario).

	Available for marine (2040-2045)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	-0,44	5,22	9,01	0,46	0,59
Middle Africa	0,00	0,00	-1,64	0,63	0,69	0,23	0,16
Northern Africa	0,00	0,00	-2,11	3,19	7,28	1,35	0,60
Southern Africa	0,00	0,00	-2,25	0,85	4,62	0,85	-0,37
Western Africa	0,00	0,00	-1,09	5,86	10,00	0,38	0,82
Northern America	-3,21	-0,98	26,88	21,28	8,56	1,48	0,61
Central America	-0,30	-0,04	-0,38	2,10	2,90	0,22	0,18
South America	0,19	-0,13	1,61	23,82	46,22	0,53	1,15
Central Asia	-0,09	-0,06	-3,33	1,50	0,59	1,58	-0,90
Eastern Asia	-0,16	1,06	-2,28	37,83	-1,12	2,56	0,55
Southern Asia	0,54	0,09	0,53	25,48	-1,16	22,94	1,45
South-eastern Asia	-0,42	-0,02	1,10	17,95	-0,12	3,63	0,82
Western Asia	-0,02	-0,01	-0,46	3,16	0,75	1,06	1,01
Oceania	-0,06	-0,02	5,18	3,57	10,25	5,97	0,86
Eastern Europe	2,70	-0,51	13,18	12,23	20,29	0,31	-0,01
Northern Europe	-0,54	-0,26	5,18	0,25	0,29	2,98	-1,28
Southern Europe	-0,69	-0,33	1,84	2,53	0,97	0,63	0,38
Western Europe	-1,18	-0,63	5,57	4,13	0,36	-0,31	-3,08

Table B.72: Projected biomass availability for the maritime industry (LS scenario).

	Available for marine (2045-2050)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	-0,26	5,90	9,89	0,47	0,86
Middle Africa	0,00	0,00	-1,43	0,85	0,76	0,24	0,36
Northern Africa	0,00	0,00	-1,88	3,45	7,61	1,35	0,87
Southern Africa	0,00	0,00	-2,03	1,09	5,08	0,85	-0,24
Western Africa	0,00	0,00	-0,89	6,60	10,99	0,39	1,12
Northern America	-3,44	-1,05	26,05	21,51	8,52	1,36	0,55
Central America	-0,32	-0,04	-0,34	2,20	2,98	0,22	0,24
South America	0,40	-0,14	1,56	24,67	47,77	0,54	1,31
Central Asia	-0,09	-0,06	-3,03	1,72	0,62	1,58	-0,79
Eastern Asia	-0,18	1,12	-2,26	38,32	-1,40	2,57	0,58
Southern Asia	0,58	0,09	0,59	26,76	-1,33	22,93	1,73
South-eastern Asia	-0,52	-0,02	1,14	18,84	-0,17	3,63	0,95
Western Asia	-0,02	-0,01	-0,40	3,32	0,78	1,05	1,09
Oceania	-0,06	-0,03	5,05	3,62	10,39	5,95	0,93
Eastern Europe	3,38	-0,56	12,84	12,40	20,53	0,28	-0,11
Northern Europe	-0,59	-0,29	4,94	0,16	0,17	2,89	-1,42
Southern Europe	-0,75	-0,37	1,77	2,55	0,95	0,55	0,30
Western Europe	-1,30	-0,69	5,32	4,12	0,29	-0,55	-3,51

B.4. High Supply (HS) scenario

For the High Supply (HS) scenario, a more optimistic estimation of biomass availability and less competition are considered. Still, taking competition of the road and aviation industry into account, availability of oils and fats seems very limited. Forestry residues and solid waste also result in negative values for some areas. This is mainly caused by the use of these feedstocks for traditional biomass use in several areas.

Table B.73: Projected biomass availability for the maritime industry (HS scenario).

	Available for marine (2020-2025)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	4,77	6,01	7,18	0,47	-0,27
Middle Africa	0,00	0,00	-0,18	0,56	0,55	0,25	-0,54
Northern Africa	0,00	0,00	-2,09	4,62	7,06	1,41	-0,26
Southern Africa	0,00	0,00	-2,66	0,83	3,68	0,82	-0,87
Western Africa	0,00	0,00	2,10	6,76	7,97	0,39	-0,12
Northern America	-0,90	0,52	129,71	40,08	10,63	2,73	2,00
Central America	-0,17	0,00	3,05	3,60	2,63	0,21	-0,06
South America	0,15	0,07	17,98	36,33	41,05	0,56	0,54
Central Asia	0,02	-0,01	-4,30	2,37	0,59	1,73	-1,37
Eastern Asia	0,35	1,43	16,48	65,11	1,47	2,65	2,15
Southern Asia	0,57	0,40	23,50	39,24	0,50	23,72	0,49
South-eastern Asia	0,30	0,14	14,46	26,83	0,50	4,04	0,46
Western Asia	0,04	0,03	0,68	4,75	0,68	1,29	0,74
Oceania	-0,01	0,09	22,21	6,03	9,44	6,08	0,63
Eastern Europe	1,82	-0,19	61,86	21,60	23,23	0,59	1,02
Northern Europe	-0,25	-0,09	29,23	2,64	1,72	3,86	0,13
Southern Europe	-0,31	-0,14	11,18	5,00	1,62	1,38	1,05
Western Europe	-0,60	-0,28	26,49	8,10	1,30	1,67	0,62

Table B.74: Projected biomass availability for the maritime industry (HS scenario).

	Available for marine (2025-2030)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	2,91	7,12	8,07	0,55	0,09
Middle Africa	0,00	0,00	-0,52	0,99	0,62	0,32	-0,23
Northern Africa	0,00	0,00	-1,85	5,25	7,56	1,56	0,09
Southern Africa	0,00	0,00	-2,25	1,29	4,14	0,78	-0,61
Western Africa	0,00	0,00	1,06	7,97	8,97	0,47	0,25
Northern America	-1,22	0,39	88,54	40,76	9,88	2,25	0,96
Central America	-0,18	0,00	1,71	3,85	2,65	0,21	0,06
South America	0,78	0,06	11,31	39,05	43,89	0,52	0,82
Central Asia	0,00	-0,02	-3,56	2,93	0,59	2,00	-1,07
Eastern Asia	0,46	1,55	8,83	67,63	-0,14	2,75	0,71
Southern Asia	0,72	0,44	14,26	41,68	-0,66	24,84	0,92
South-eastern Asia	0,64	0,14	9,16	28,75	0,09	4,62	0,58
Western Asia	0,05	0,03	0,31	5,17	0,70	1,41	0,84
Oceania	-0,02	0,08	15,35	6,23	9,76	6,00	0,70
Eastern Europe	2,75	-0,24	42,34	22,22	23,76	0,44	0,35
Northern Europe	-0,27	-0,10	19,35	2,07	1,01	3,54	-0,85
Southern Europe	-0,34	-0,16	7,42	5,01	1,44	1,07	0,62
Western Europe	-0,61	-0,31	17,92	7,97	0,89	0,33	-1,90

Table B.75: Projected biomass availability for the maritime industry (HS scenario).

	Available for marine (2030-2035)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	2,56	8,17	8,95	0,63	0,42
Middle Africa	0,00	0,00	-0,34	1,38	0,68	0,41	0,06
Northern Africa	0,00	0,00	-1,46	5,77	7,99	1,72	0,43
Southern Africa	0,00	0,00	-1,81	1,71	4,59	0,74	-0,38
Western Africa	0,00	0,00	1,00	9,11	9,95	0,58	0,61
Northern America	-1,63	0,21	74,09	41,21	9,37	2,36	0,93
Central America	-0,19	-0,01	1,39	4,11	2,74	0,22	0,16
South America	1,71	0,06	9,31	41,27	46,18	0,54	1,07
Central Asia	-0,01	-0,03	-2,93	3,36	0,59	2,32	-0,83
Eastern Asia	0,59	1,67	6,82	69,67	-0,62	2,88	0,77
Southern Asia	0,90	0,48	11,72	44,31	-0,95	26,09	1,39
South-eastern Asia	1,10	0,14	7,63	30,54	-0,03	5,34	0,79
Western Asia	0,05	0,02	0,27	5,49	0,72	1,62	0,95
Oceania	-0,04	0,08	12,97	6,38	9,98	5,98	0,78
Eastern Europe	4,13	-0,31	35,63	22,67	24,13	0,41	0,26
Northern Europe	-0,31	-0,12	16,05	1,97	0,82	3,61	-1,05
Southern Europe	-0,38	-0,19	6,15	5,08	1,37	1,11	0,53
Western Europe	-0,63	-0,34	14,93	8,02	0,76	-0,02	-2,54

Table B.76: Projected biomass availability for the maritime industry (HS scenario).

	Available for marine (2035-2040)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	2,86	9,19	9,84	0,73	0,75
Middle Africa	0,00	0,00	0,04	1,73	0,75	0,52	0,33
Northern Africa	0,00	0,00	-1,06	6,21	8,35	1,91	0,76
Southern Africa	0,00	0,00	-1,40	2,09	5,05	0,71	-0,18
Western Africa	0,00	0,00	1,34	10,23	10,93	0,70	0,97
Northern America	-2,01	0,03	71,70	41,18	8,72	2,46	0,80
Central America	-0,20	-0,02	1,43	4,27	2,77	0,23	0,25
South America	3,06	0,05	9,13	42,66	47,59	0,55	1,29
Central Asia	-0,03	-0,05	-2,41	3,72	0,59	2,69	-0,63
Eastern Asia	0,80	1,80	6,68	70,43	-1,23	3,02	0,65
Southern Asia	1,15	0,53	11,72	46,37	-1,31	27,40	1,78
South-eastern Asia	1,70	0,15	7,61	31,97	-0,17	6,18	0,97
Western Asia	0,05	0,02	0,36	5,75	0,73	1,87	1,05
Oceania	-0,05	0,07	12,65	6,46	10,10	5,96	0,86
Eastern Europe	6,20	-0,37	34,69	22,86	24,26	0,38	0,10
Northern Europe	-0,34	-0,14	15,47	1,79	0,56	3,67	-1,32
Southern Europe	-0,42	-0,21	5,94	5,07	1,27	1,14	0,41
Western Europe	-0,64	-0,37	14,36	7,97	0,59	-0,44	-3,33

Table B.77: Projected biomass availability for the maritime industry (HS scenario).

	Available for marine (2040-2045)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	3,09	10,27	11,01	0,85	1,08
Middle Africa	0,00	0,00	0,33	2,07	0,84	0,66	0,59
Northern Africa	0,00	0,00	-0,73	6,64	8,82	2,11	1,09
Southern Africa	0,00	0,00	-1,06	2,47	5,65	0,67	0,00
Western Africa	0,00	0,00	1,60	11,41	12,23	0,84	1,34
Northern America	-2,12	-0,04	69,51	41,35	8,32	2,54	0,56
Central America	-0,20	-0,02	1,44	4,41	2,82	0,25	0,33
South America	5,03	0,05	8,83	44,05	49,38	0,55	1,49
Central Asia	-0,03	-0,06	-1,97	4,06	0,60	3,12	-0,47
Eastern Asia	1,14	1,98	6,33	71,09	-1,89	3,16	0,34
Southern Asia	1,46	0,58	11,50	48,40	-1,74	28,77	2,13
South-eastern Asia	2,49	0,16	7,51	33,43	-0,32	7,15	1,11
Western Asia	0,07	0,02	0,43	6,02	0,75	2,15	1,15
Oceania	-0,06	0,07	12,33	6,54	10,26	5,93	0,94
Eastern Europe	9,33	-0,41	33,78	23,10	24,52	0,34	-0,13
Northern Europe	-0,34	-0,16	14,84	1,57	0,28	3,70	-1,67
Southern Europe	-0,42	-0,23	5,74	5,07	1,20	1,16	0,25
Western Europe	-0,61	-0,39	13,79	7,91	0,42	-0,96	-4,29

Table B.78: Projected biomass availability for the maritime industry (HS scenario).

	Available for marine (2045-2050)						
	Vegetable oils	**Waste oils**	**Forestry residues**	**Agricultural residues**	**Energy crops**	**Liquid waste**	**Solid waste**
Eastern Africa	0,00	0,00	3,25	11,42	11,87	0,99	1,43
Middle Africa	0,00	0,00	0,57	2,42	0,91	0,83	0,86
Northern Africa	0,00	0,00	-0,47	7,06	9,14	2,33	1,44
Southern Africa	0,00	0,00	-0,80	2,86	6,09	0,64	0,17
Western Africa	0,00	0,00	1,80	12,68	13,19	1,02	1,73
Northern America	-1,95	-0,01	67,52	41,73	8,07	2,59	0,18
Central America	-0,18	-0,02	1,40	4,53	2,82	0,26	0,40
South America	7,88	0,05	8,43	45,41	50,46	0,55	1,67
Central Asia	-0,01	-0,06	-1,61	4,40	0,62	3,61	-0,34
Eastern Asia	1,63	2,19	5,78	71,64	-2,65	3,31	-0,17
Southern Asia	1,87	0,64	11,05	50,40	-2,28	30,20	2,42
South-eastern Asia	3,53	0,18	7,33	34,91	-0,50	8,27	1,22
Western Asia	0,11	0,02	0,49	6,30	0,77	2,48	1,24
Oceania	-0,06	0,07	12,01	6,62	10,36	5,90	1,03
Eastern Europe	13,95	-0,43	32,90	23,36	24,67	0,29	-0,44
Northern Europe	-0,33	-0,16	14,16	1,29	-0,05	3,70	-2,12
Southern Europe	-0,40	-0,24	5,53	5,07	1,12	1,16	0,04
Western Europe	-0,55	-0,41	13,22	7,84	0,24	-1,60	-5,47

C
Demand scenarios

To estimate the future energy demand of the shipping sector, the Third IMO GHG study is used as a starting point. Tables C.3 and C.2 show the base assumptions for the development of these scenarios. The chosen scenarios in this thesis are bold in table C.1.

Table C.1: The scenarios used in this thesis are made bold. Scenario 11, 8 and 14 correspond to the low, base and high demand scenarios respectively.

Scenario	RCP scenario	SSP scenario	Fuel mix (LNG, ECA)	Efficiency improvement 2050
1	RCP8.5	SSP5	high LNG/extra ECA	High
2	RCP6.0	SSP1	high LNG/extra ECA	High
3	RCP4.5	SSP3	high LNG/extra ECA	High
4	RCP2.6	SSP4	high LNG/extra ECA	High
5	RCP8.5	SSP5	high LNG/extra ECA	low
6	RCP6.0	SSP1	high LNG/extra ECA	low
7	RCP4.5	SSP3	high LNG/extra ECA	low
8	**RCP2.6**	**SSP4**	**high LNG/extra ECA**	**low**
9	RCP8.5	SSP5	low LNG/no ECA	High
10	RCP6.0	SSP1	low LNG/no ECA	High
11	**RCP4.5**	**SSP3**	**low LNG/no ECA**	**High**
12	RCP2.6	SSP4	low LNG/no ECA	High
13 (BAU)	RCP8.5	SSP5	low LNG/no ECA	low
14 (BAU)	**RCP6.0**	**SSP1**	**low LNG/no ECA**	**low**
15 (BAU)	RCP4.5	SSP3	low LNG/no ECA	low
16 (BAU)	RCP2.6	SSP4	low LNG/no ECA	low

Table C.2: RCP used in the Third IMO GHG Study.

RCP	**Decription**
RCP2.6	Peak in radiative forcing at ~3 W/m2 before 2100 and decline
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m2 at stabilization after 2100
RCP6.0	Stabilization without overshoot pathway to 6 W/m2 at stabilization after 2100
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m2 in 2100

Table C.3: SSP scenarios from the Third IMO GHG Study [124]

SSP number and name	Short narrative
SSP1: Sustainability	A world making relatively good progress towards sustainability, with ongoing efforts to achieve development goals while reducing resource intensity and fossil fuel dependency. It is an environmentally aware world with rapid technology development and strong economic growth, even in low-income countries.
SSP2: Middle of the road	A world that sees the trends typical of recent dECAdes continuing, with some progress towards achieving development goals. Dependency on fossil fuels is slowly decreasing. Development of low-income countries proceeds unevenly.
SSP3: Fragmentation	A world that is separated into regions characterized by extreme poverty, pockets of moderate wealth and a large number of countries struggling to maintain living standards for a rapidly growing population.
SSP4: Inequality	A highly unequal world in which a relatively small, rich global elite is responsible for most GHG emissions, while a larger, poor group that is vulnerable to the impact of climate changes contributes little to the harmful emissions. Mitigation efforts are low and adaptation is difficult due to ineffective institutions and the low income of the large poor population.
SSP5: Conventional development	A world in which development is oriented towards economic growth as the solution to social and economic problems. Rapid conventional development leads to an energy system dominated by fossil fuels, resulting in high GHG emissions and challenges to mitigation.

D

Refinery parameters

This appendix contains supporting information regarding the economic processing and upgrading parameters used in the model runs.

D.1. Processing costs

In the following figures, processing costs for Fast-Pyrolysis, Hydrothermal Liquefaction and Gasification Fischer-Tropsch are presented. These values are obtained from various literature sources. Costs are split up into capital investment, fixed and variable costs.

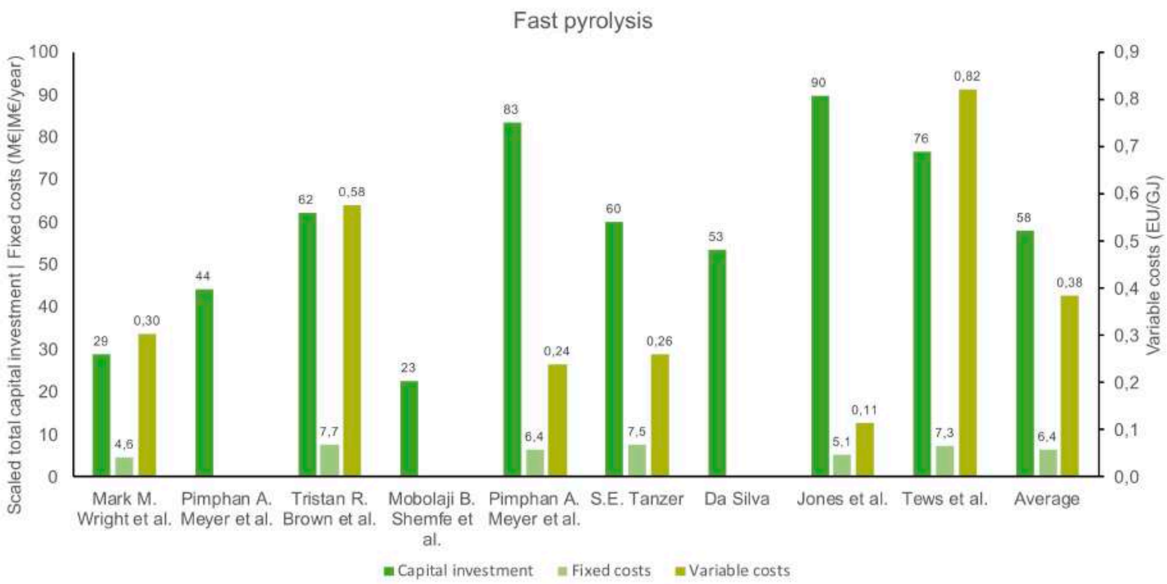

Figure D.1: Expenses related to fast-pyrolysis of biomass to bio-oil. [31, 36, 84, 102, 103, 120, 126, 127, 141]

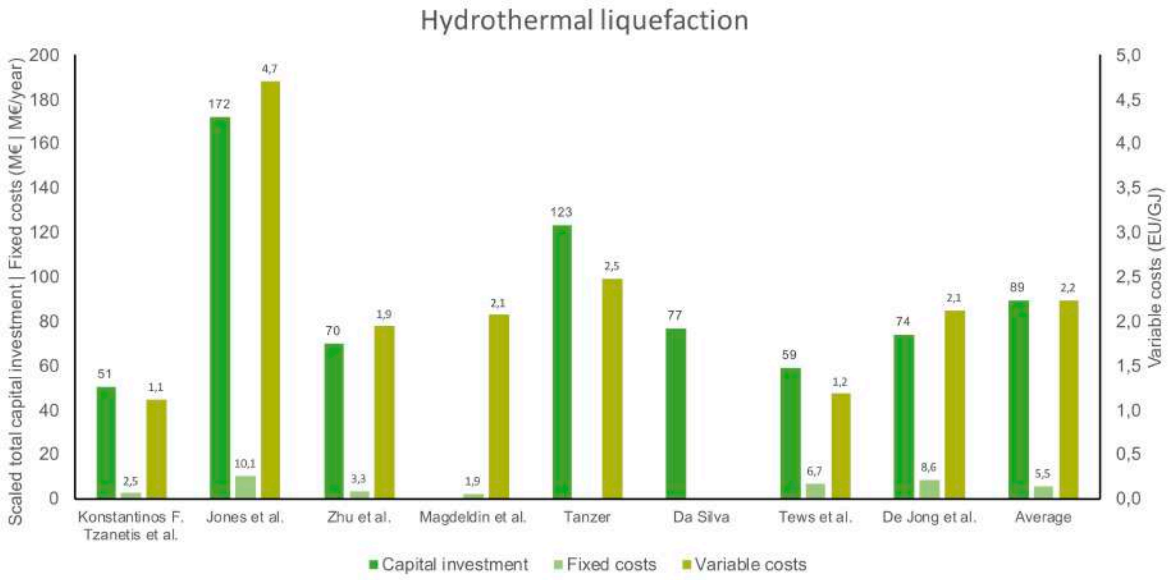

Figure D.2: Expenses related to HTL of biomass to bio-crude. [36, 43, 84, 96, 126, 127, 129, 143]

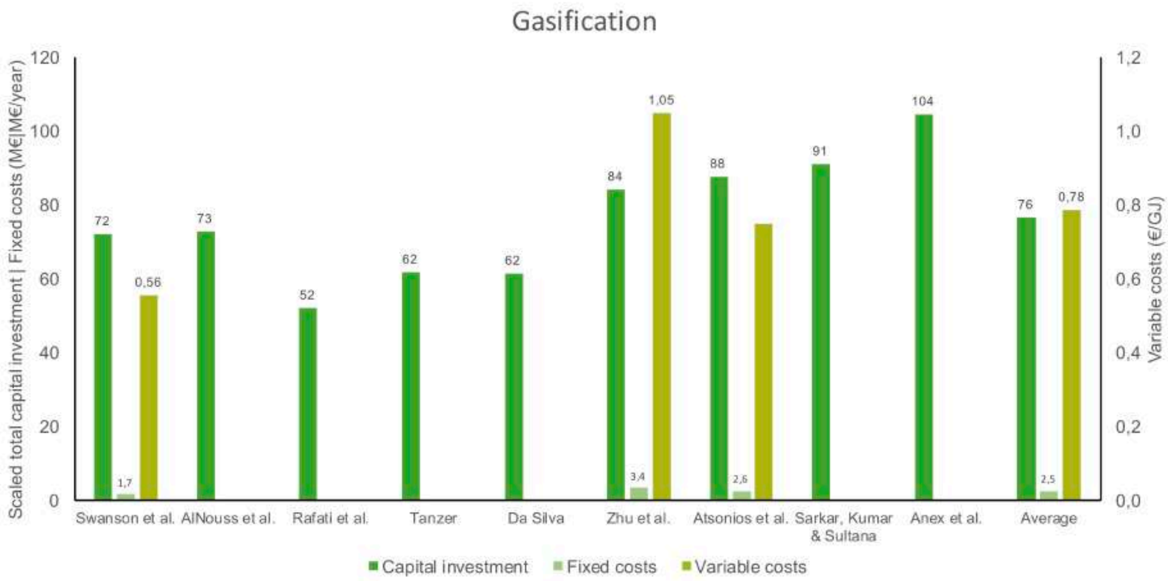

Figure D.3: Expenses related to gasification of biomass to syngas. [19, 22, 24, 36, 115, 117, 125, 126, 143]

D.2. Upgrading costs

This section contains a comparison of literature outcomes on the economic performance of upgrading of the previously mentioned advanced biofuel technologies.

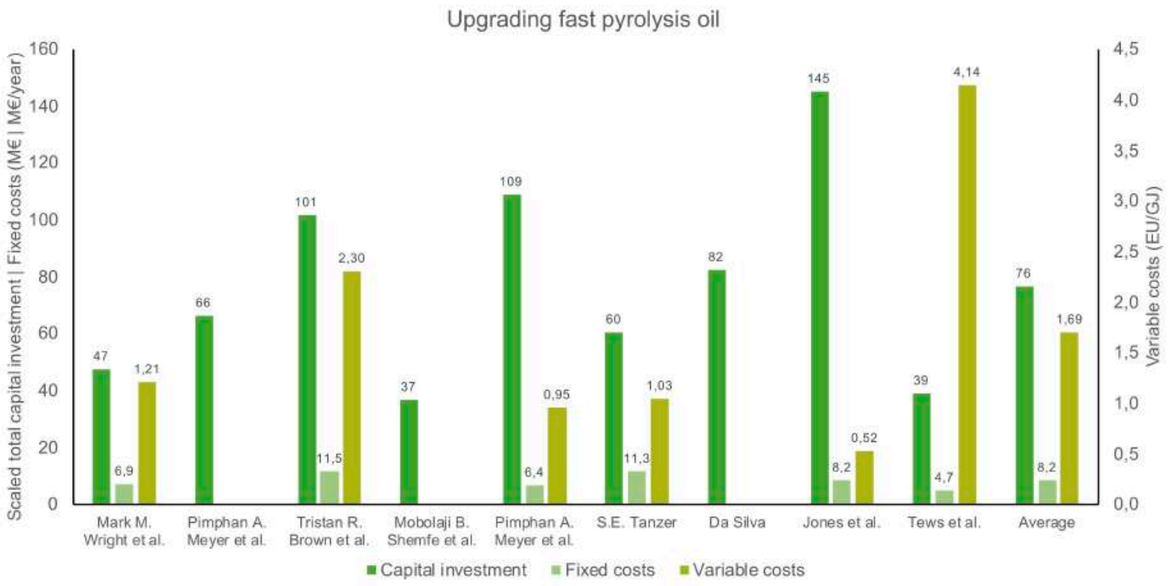

Figure D.4: Expenses related to the upgrading of bio-oil. [31, 36, 84, 102, 103, 120, 126, 127, 141]

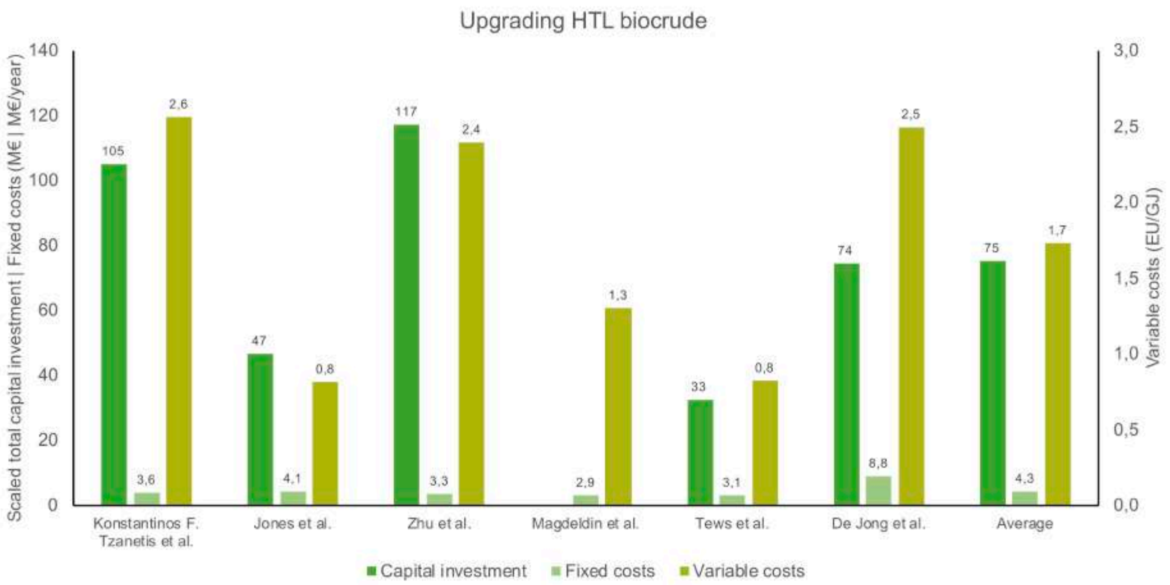

Figure D.5: Expenses related to the upgrading of bio-crude. [36, 43, 84, 96, 126, 127, 129, 143]

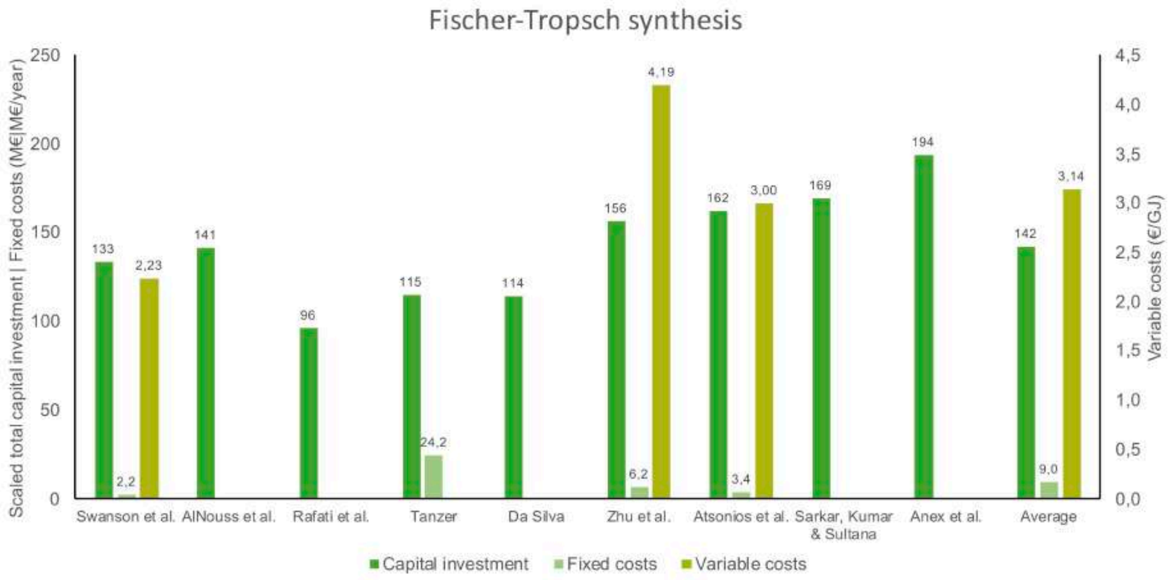

Figure D.6: Expenses related to Fischer-Tropsch synthesis of syngas. [19, 22, 24, 36, 115, 117, 125, 126, 143]

E

Model testing

This appendix contains some supplementary information regarding the testing of the base case scenario. Section E.1 shows the sensitivity analysis performed on isolated objectives. Trade flows for the isolated objectives were not included in the main text, but can be viewed in section E.2.

E.1. Sensitivity analysis

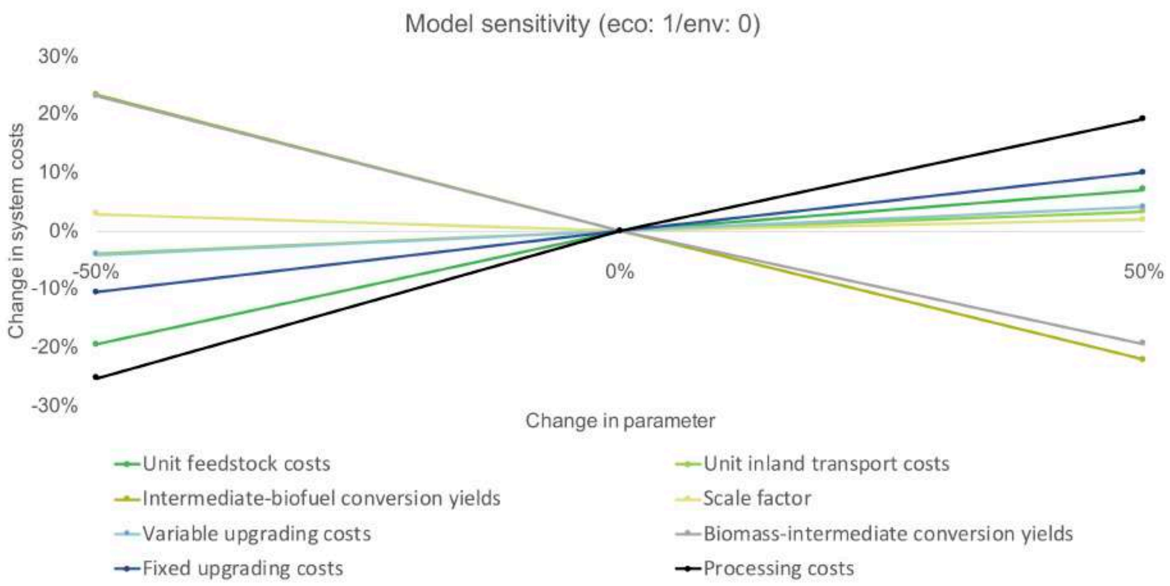

Figure E.1: Impact of parameter values on system costs, only including economic objective.

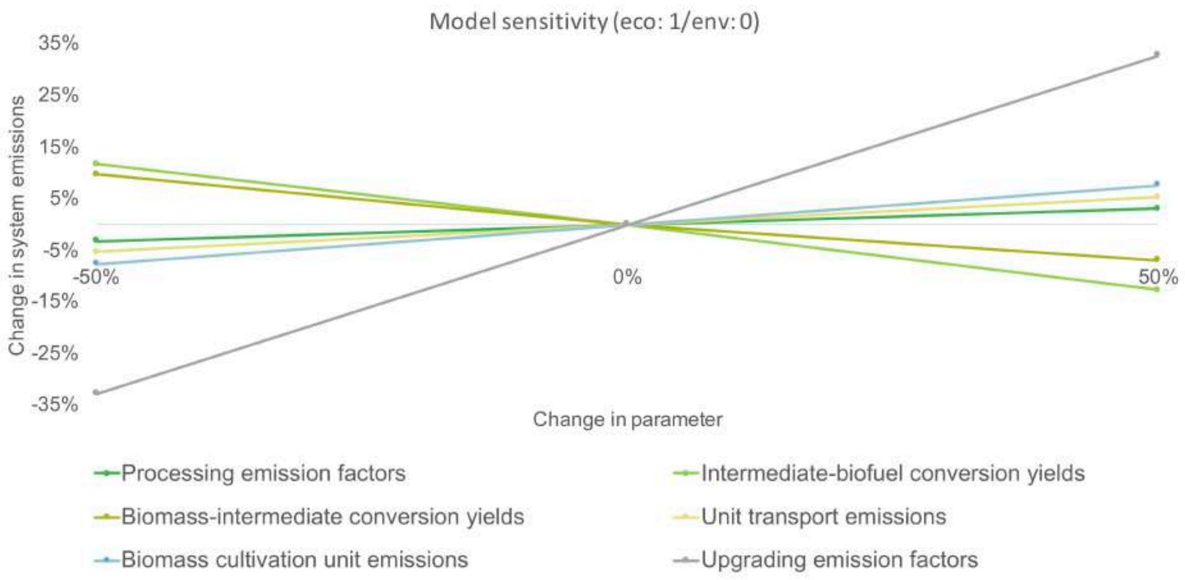

Figure E.2: Impact of parameter values on system emissions, only including economic objective.

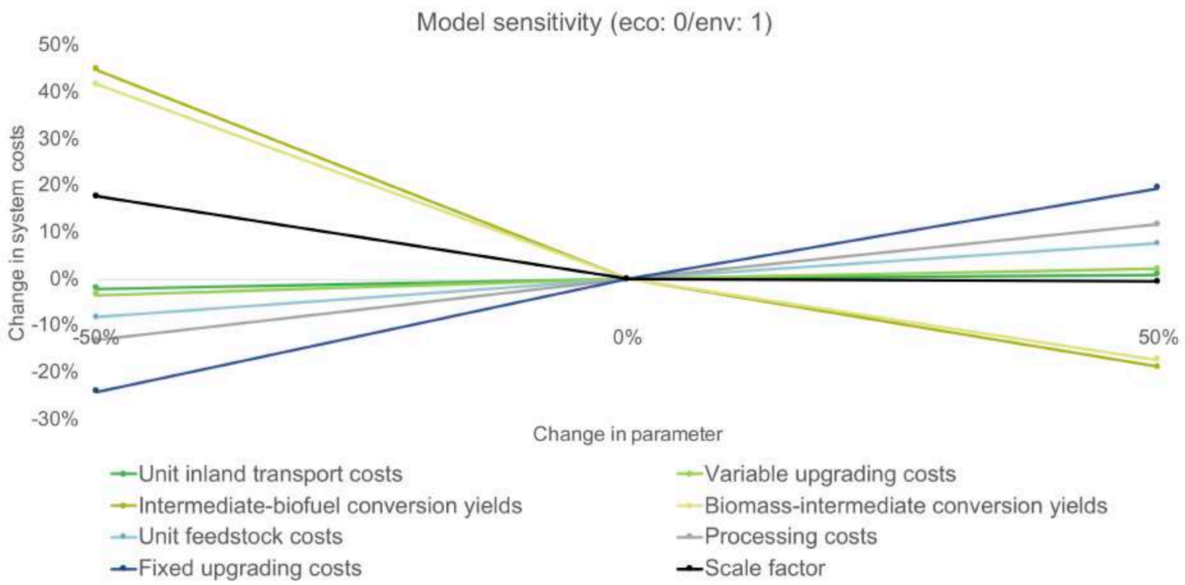

Figure E.3: Impact of parameter values on system costs, only including environmental objective.

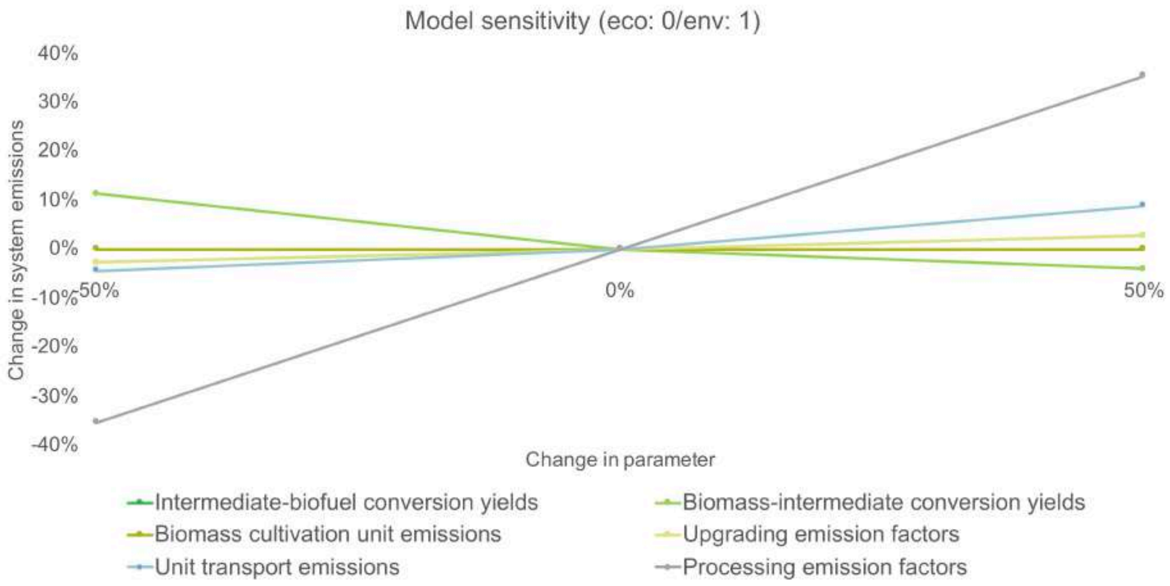

Figure E.4: Impact of parameter values on system emissions, only including environmental objective.

E.2. Trade-off economic and environmental performance

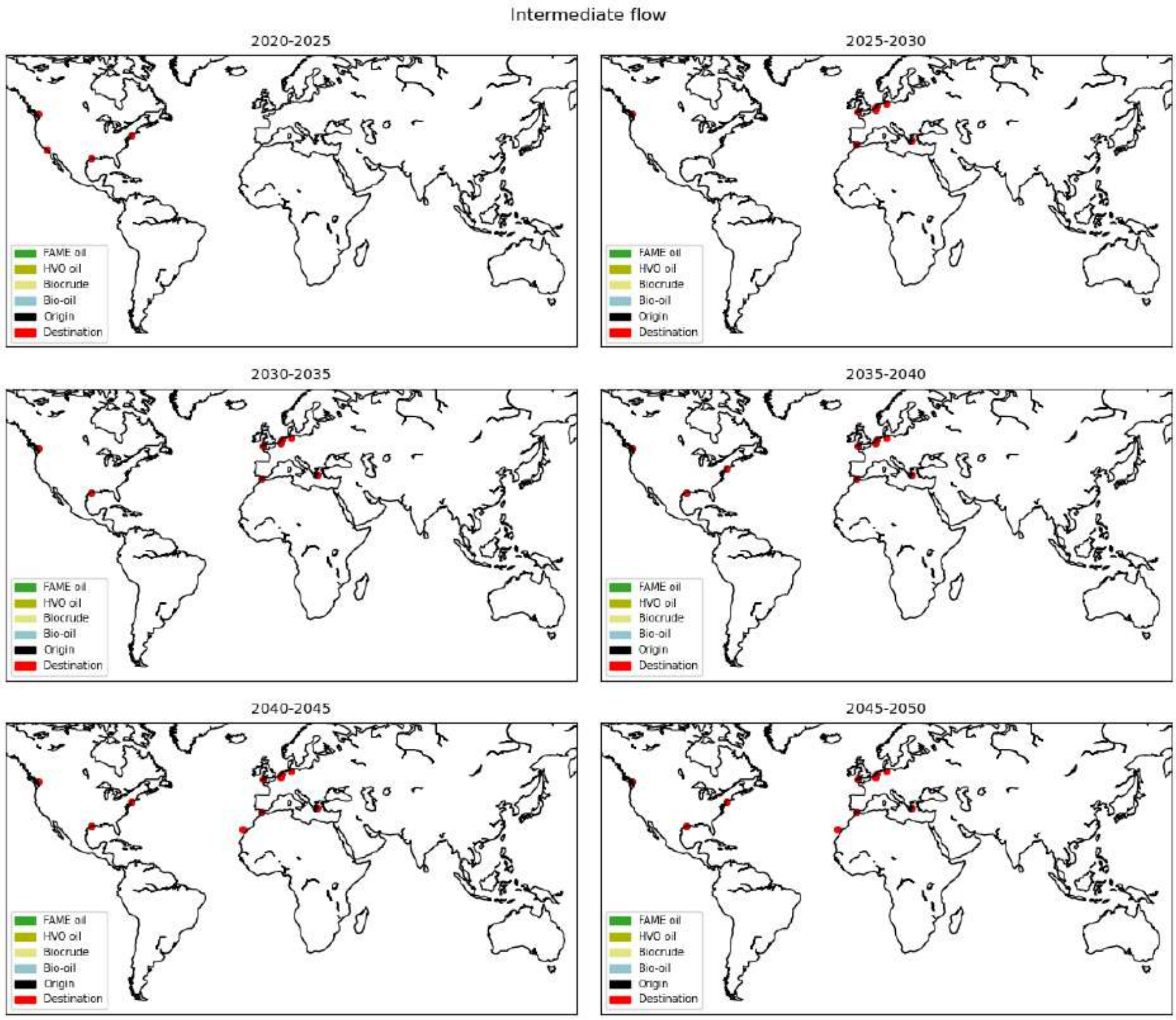

Figure E.5: Optimal flow of intermediate products for weight set of Eco: 0 and Env: 1

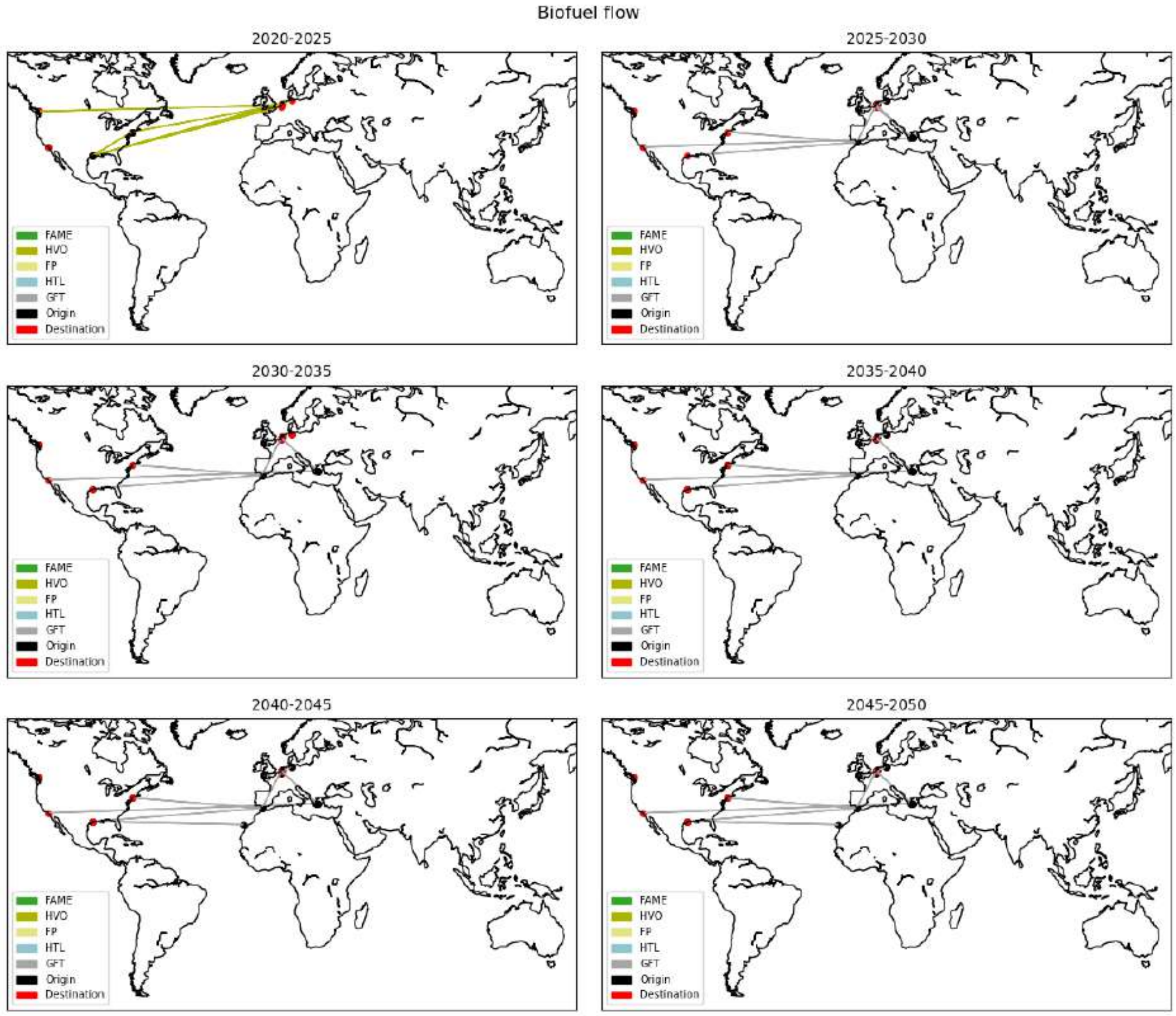

Figure E.6: Optimal flow of biofuel products for weight set of Eco: 0 and Env: 1

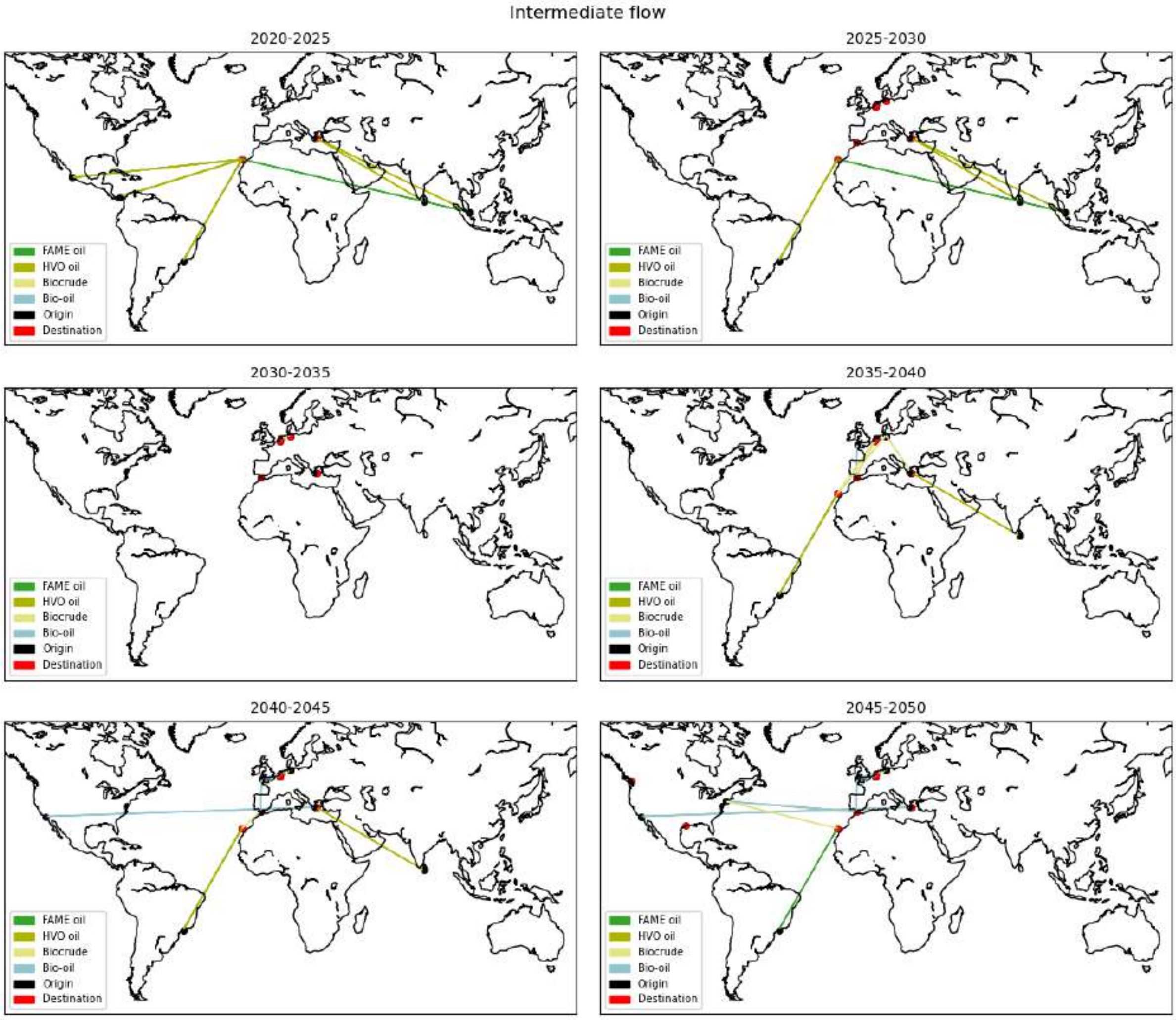

Figure E.7: Optimal flow of intermediate products for weight set of Eco: 1 and Env: 0

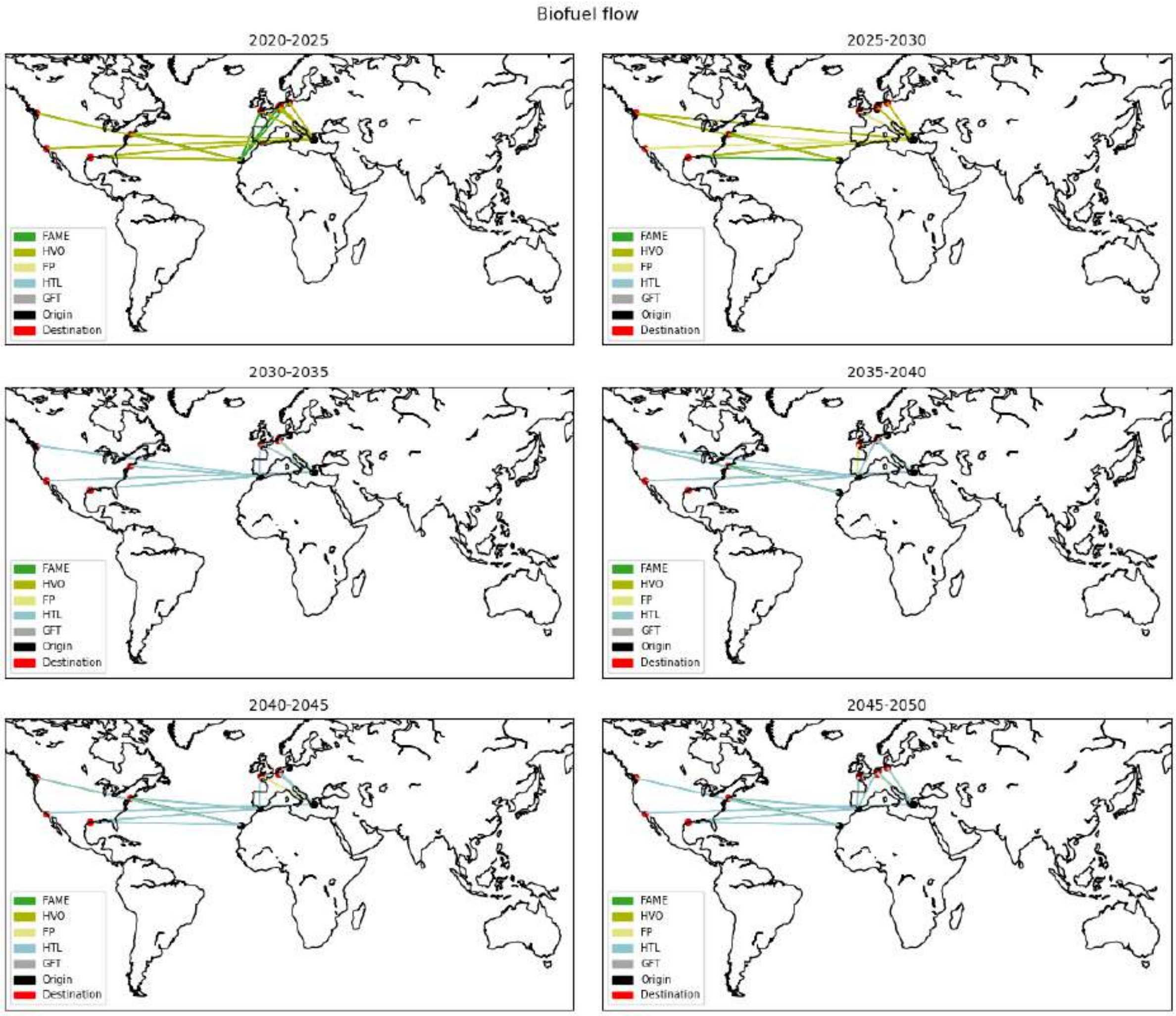

Figure E.8: Optimal flow of biofuel products for weight set of Eco: 1 and Env: 0

F

Scenario analysis: costs and emissions

In this appendix, the costs and emission graphs for the scenarios which were not included in the main text are shown.

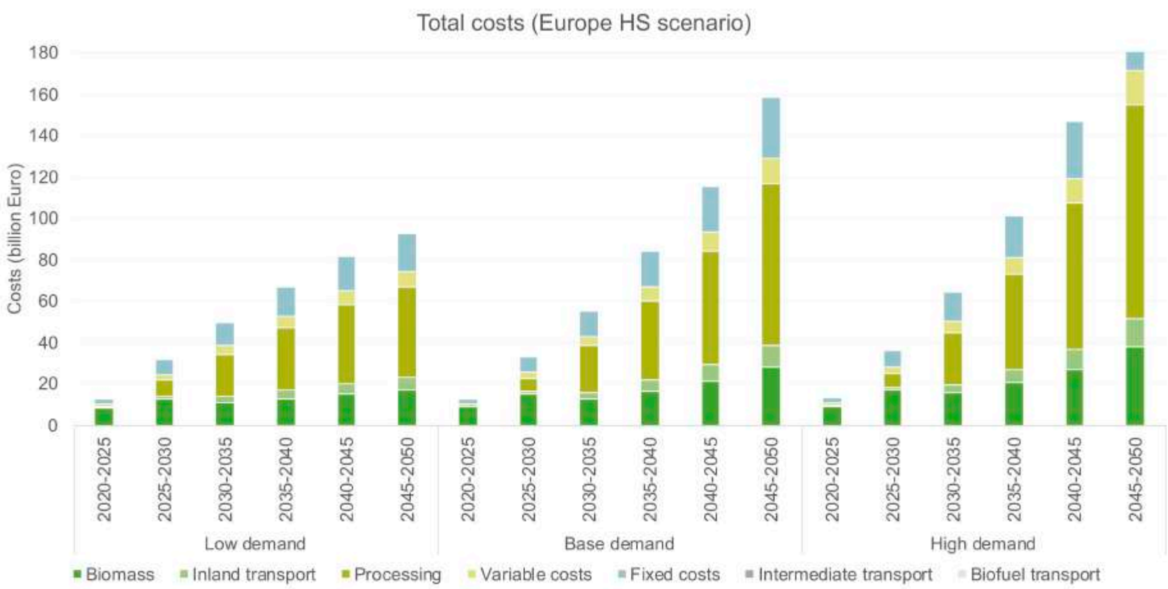

Figure F.1: Total system costs in Europe HS scenario.

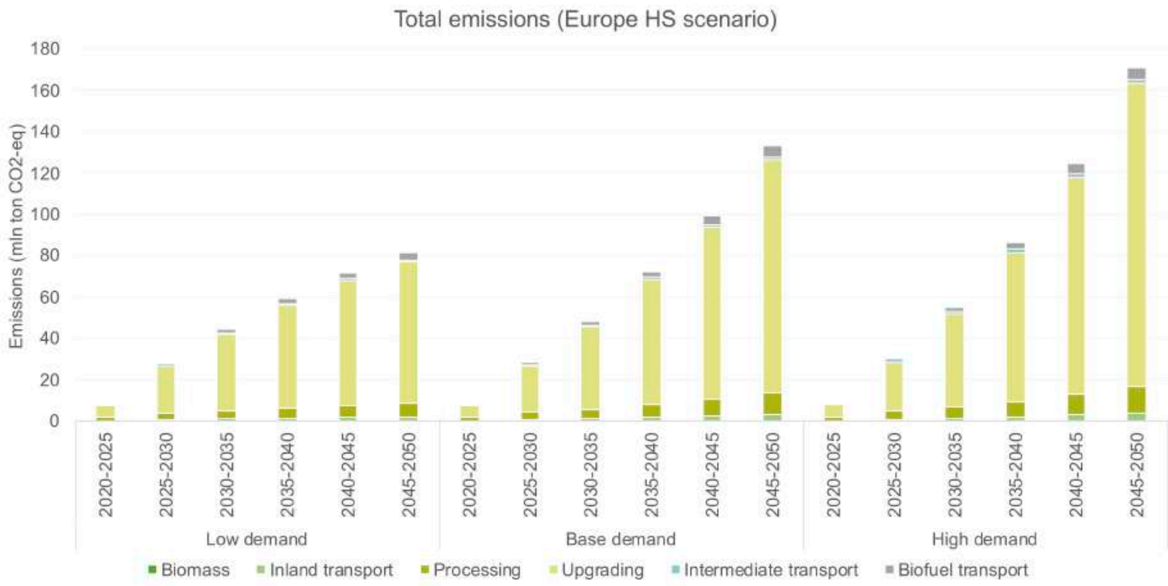

Figure F.2: Total emissions costs in Europe HS scenario.

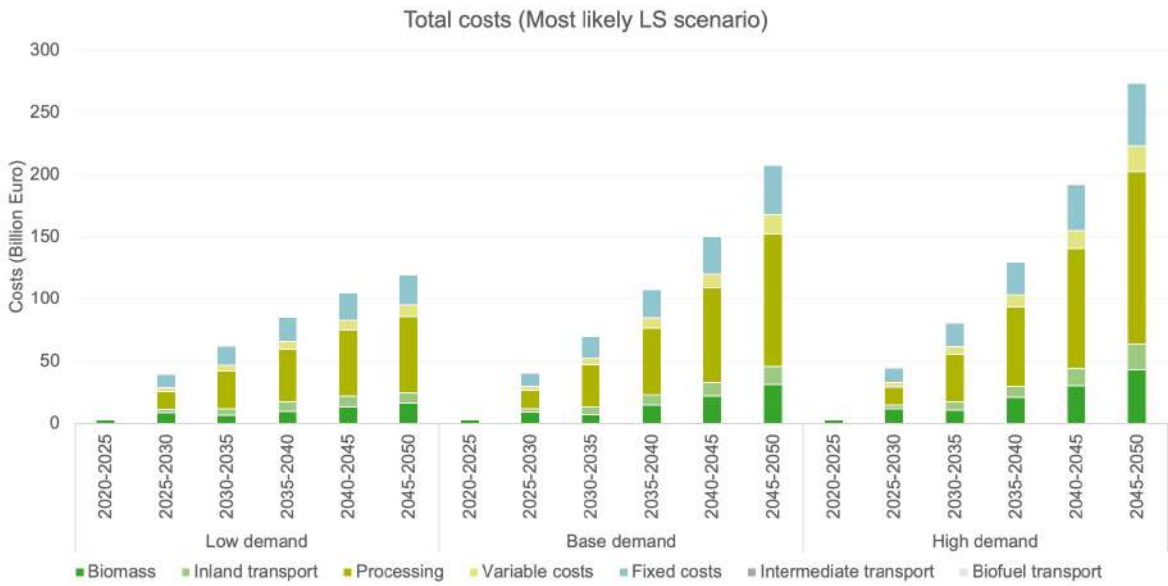

Figure F.3: Total system costs in the ML LSBD scenario.

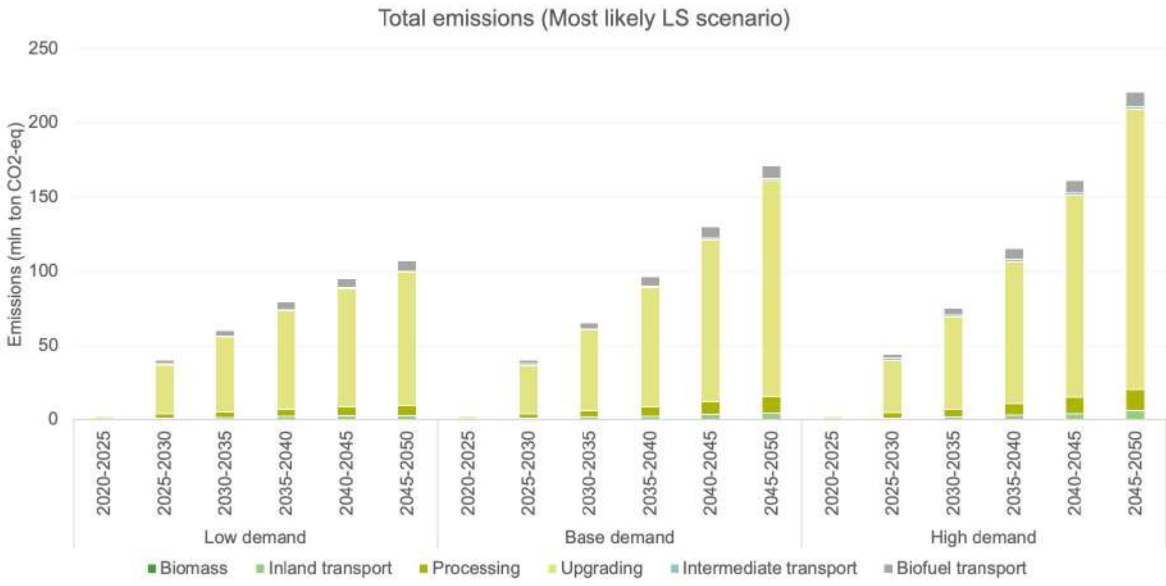

Figure F.4: Total system emissions in the ML LSBD scenario.

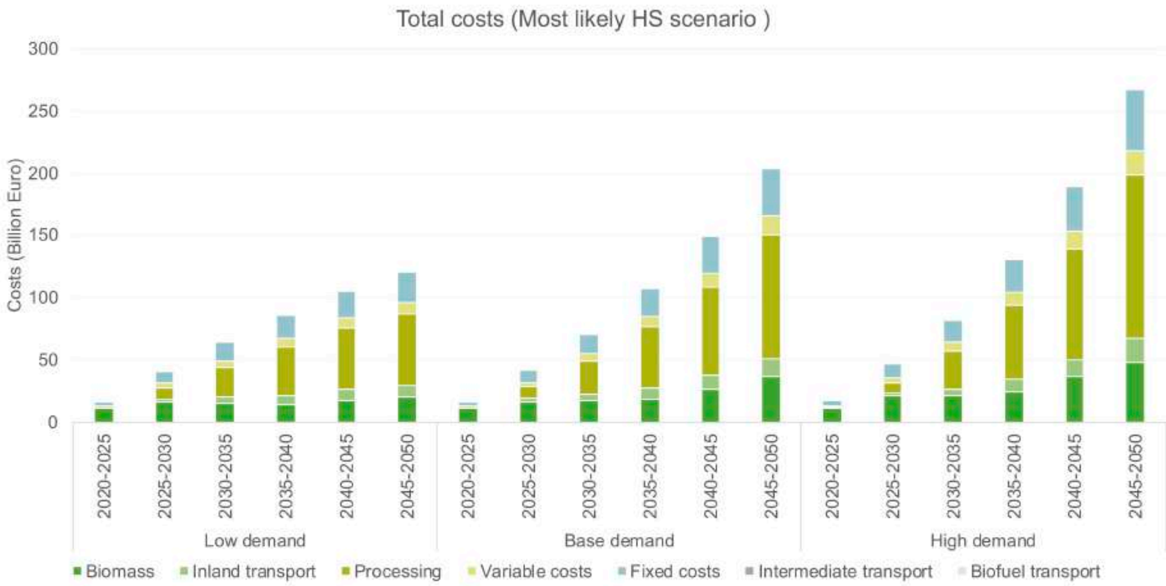

Figure F.5: Total system costs in the ML HSBD scenario.

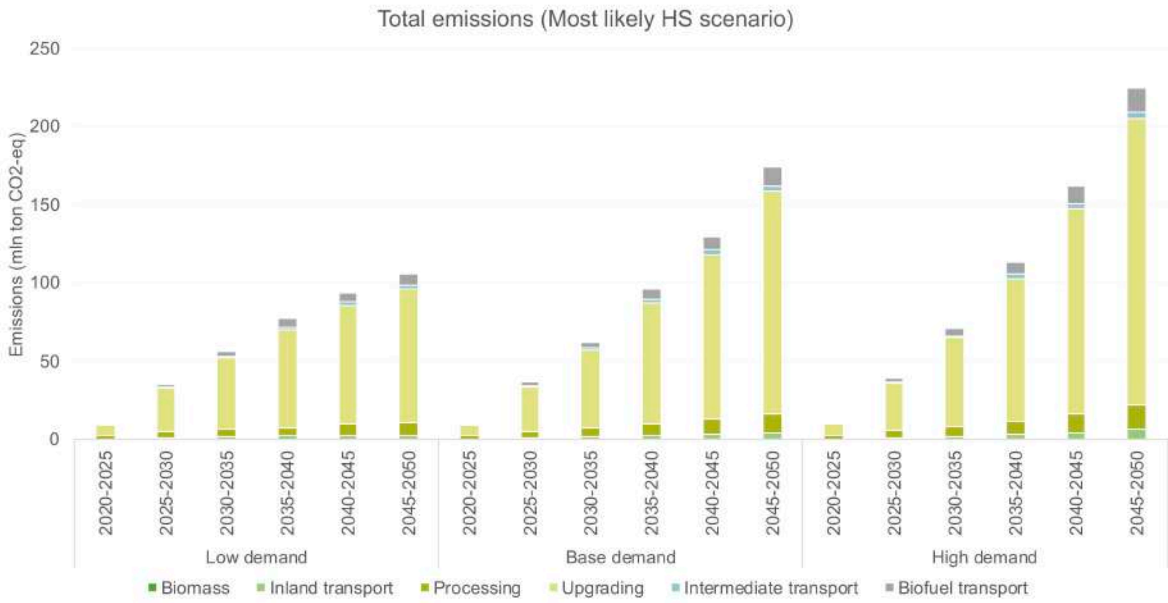

Figure F.6: Total system emissions in the ML HSBD scenario.

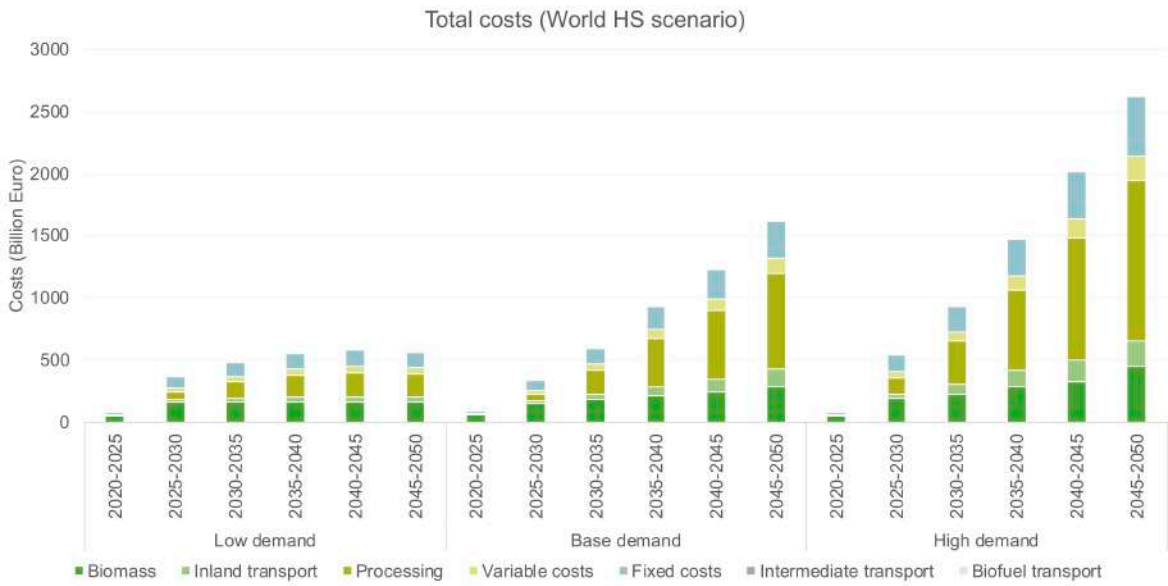

Figure F.7: Total system costs in the World HSBD scenario.

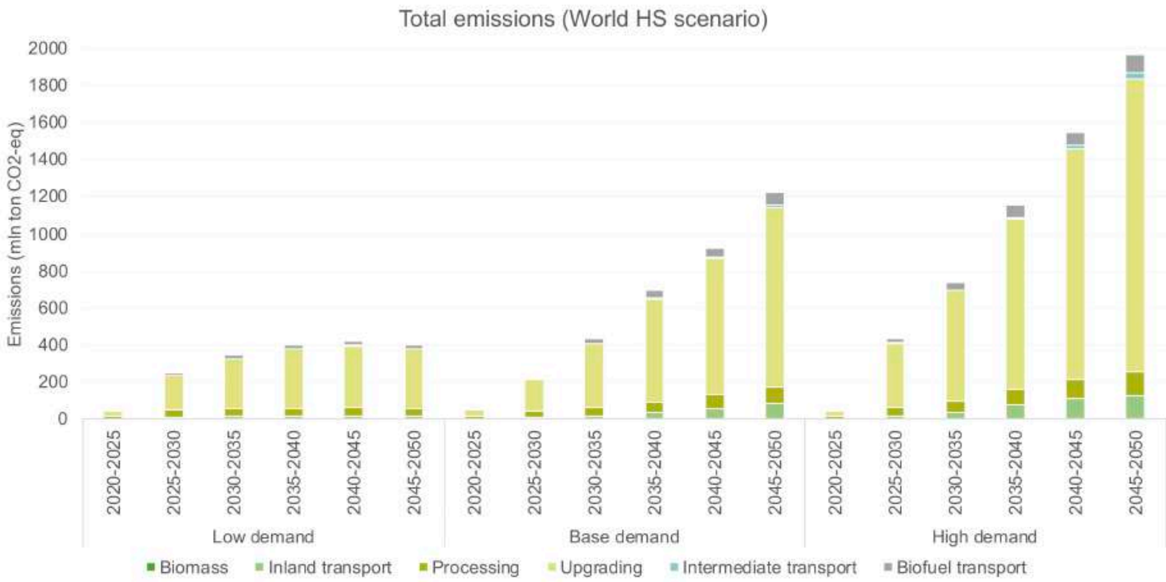

Figure F.8: Total system emissions in the World HSBD scenario.

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