European Production of Biofuels for the Maritime Industry

A MILP optimization of biofuel supply chains to minimize costs and emissions for the first phase of the Energy Transition.

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by

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TU Delft

Summary

The maritime industry has long relied on oils and heavy fuels as main energy carriers. Though one of the most efficient modes of transport (in terms of costs and emissions per tonne mile), the shipping sector still accounts for an important 2.5% of global greenhouse gas emissions. On top of this, current industry fuels have high levels of sulfur and release nitrogen oxides upon combustion, which both can be extremely harmful to local environments and ecosystems. The largest body in marine regulation; The International Maritime Organization (IMO) has set a goal in reducing total industry emissions to 50% relative to 2008 levels. Additionally, the European Union has passed a series of regulations and targets relating to shipping, and there are growing concerns (for shipoweners) on the expansion of Emission Control Areas (ECAs) across Europe. However, most of the regulations passed are not yet binding and it is not entirely clear how these goals are to be accomplished.

Over time, different methods have been proposed to abate these emissions and find more sustainable energy carrier sources for the long run. It is expected that in the long term (30+ years), onboard energy carriers will gradually shift towards hydrogen fuels and electric batteries. However, there is still a critical need for short-to-medium term technologies to solve this issue. One of the most promising current solutions to this problem is the use of biofuels. These sustainably-sourced combustibles can cut back total emissions by considerable amounts and are supportable in the medium to long term. Past use of biofuels has been centered around drop-in fuels produced from first-generation feedstock sources largely based on oil, such as biodiesel. The benefit of these fuels revolved around their drop-in nature and the fact that they required almost no change in ship infrastructure. However, recent European regulations are trying to move away from oil-based fuels and first generation feedstocks due to Indirect Land Use Change (ILUC) concerns. Several studies have outlined alcohols (bio-methanol and bio-ethanol) as well as bio-methane as some of the best-positioned fuels for research and development.

Similar to first generation biofuels, a large concern surrounding these newly proposed fuels relate to the feedstock availability. There is much uncertainty with regards to the potential supply and production of these fuels over the ensuing years. The environmental impacts are not limited to the combustion of themselves, but also the entire life cycle and production process. The challenge with biofuels is therefore creating cost-effective supply-chains that are able to meet market demands while still reducing life-cycle emissions.

Maritime is an international industry, however, the majority of binding energy policies are set at the national level. Since many of the proposed directives and regulations are not obligatory, there is much uncertainty around what is achievable, by when, and where. The disconnect in terms of agreements, capabilities, technologies, infrastructure, funding and cooperation make this a very difficult endeavour to be achieved internationally. However, the EU has the necessary funds, ambitions, policies and cooperation to lead the global path for the development of these technologies. Therefore, it is likely that the EU will become one of the first global jurisdictions to embark on the collective effort towards decarbonizing the maritime industry.

The goal of this report is to assess the various production potentials of three specific fuels (bio-ethanol, bio-methanol and bio-LNG) in the EU and in the process point out the barriers/edges with respect to their adoption. To do so, five main activities were carried out. First, a model was developed to represent the whole production system including the most important parameters within the chosen system boundaries. Once the system was defined, the available supply of the feedstocks used for production were assessed and mapped out over the geographic area in question. Then, realistic demand scenarios were developed to match future possibilities. Once this was done, the techno-economic parameters outlining the model were defined and inputted into the system. Lastly, a sensitivity analysis along with several useful scenarios were carried out to gather information from the model.

Before a model was formulated, an in-depth literature review was performed on the subject of biofuel supply chains and in specific, optimization techniques and developments. It was determined that the problem was best characterized as a transshipment formulation and that the most useful method to solve it (from past literature) was though a Mixed Integer Linear Programming (MILP) optimization. It was chosen to model the supply chain as a series of nodes with four main echelons, starting from the collection, to the pre-treatment, to the conversion and final distribution. The pre-treatment step was included to allow for more efficient inland transport of biomass, in terms of costs and emissions. The in-scope countries included all of the EU member states (except Malta, Cyprus and Luxemburg) plus the UK, Norway and Switzerland. The countries themselves were modelled as geographically distributed point sources characterized by a set of parameters. Similarly, fifteen ports were chosen as both the refinery locations and demand points. The selection of ports was largely made based on port size, in terms of bunkering, within the in-scope countries. With the modelling framework in mind, the model could be described through a series of linear equations and constrains. As with many supply-chain optimization problems, the objective function was a minimization of costs and emissions.

Once the model had been developed and described, the supply of biomass was calculated. Available feedstocks were divided into five main categories and the theoretical and technical potentials of each was estimated. Availability factors, environmental concerns, competition and collection ratios were all considered in the calculation of each. After applying all of the technical limitations to the theoretical supply of each feedstock, the total energy amount was greatly reduced. It was discovered that biomass from purely waste sources such as biowaste and sewage had the lowest supply potentials. Three different scenarios were developed to capture the involved uncertainty in competition and future unavailability.

The fuel demand was largely estimated based on the IMO's (International Maritime Organization) fourth GHG study which outlined several worldwide bunker demand scenarios. This was used in combination with respective port energy demand and the RED II targets relating to advanced biofuel uptake. Again, the inherent uncertainty embedded in the calculation called for a more thorough analysis, thus various scenarios were developed.

Finally, with the system defined and the parameters established, the model was verified and validated, and several scenarios were run to gather data. From the sensibility analysis, it was shown that the model was specifically responsive to the electricity costs used in the pretreatment, conversion costs and specific conversion emissions. The trials showed that although most demand scenarios could be met, there was large infrastructure gaps between geographic areas resulting in higher costs/emissions and at times deficits. It was also determined that forestry residues were by far the most suitable feedstock for all cases. On average, the costs of final product ranged from 22-38 €/GJ and the emissions from 25-37 kgCO_2/GJ, which in terms of emission abatement was around 73% (compared to fossil fuel comparator as defined in the RED II) for the scenarios that were able to fulfill all demand. The costs were mainly dominated by the pretreatment and conversion process but also to a lesser extent, the biomass costs and intermediate transport. To a certain extent, the emission distribution was found to be almost completely dominated by the conversion process.

The majority of fuels were produced and shipped within the North Sea, as much of the conversion capabilities and energy demand was centered around those ports/cities. In terms of fuel production, it was found that bio-ethanol and bio-methanol were more achievable than bio-LNG due to production capacities. Moreover, the areas which showed a lack of infrastructure and incurred high deficits, were the southern-athlantic ports of Spain and Portugal. Though in general, northern economies such as Germany, the Netherlands, Sweden and Belgium were much better equipped for the production of these fuels than mediterranean economies, in terms of plant capacities.

Furthermore, the choice of most preferential feedstock proved to be forest residues, although biowaste and manure saw a considerable uptake. The choice of feedstock was also found to be tightly related to biomass prices and cost of labour/electricity of the respective country it was collected in. For this reason, a majority of biomass was collected in cheap eastern European countries nearby ports with good production infrastructure. However, there was also a significant proportion of biomass collected in small countries in which large export ports were located. Material properties such as LHV and moisture content of a certain feedstock were demonstrated to hold vital importance in the selection as well, for transportation concerns.

The report showed, through its assumptions and formulation, that the use of the fuels can be viable in the foreseeable future. As of now, ethanol and methanol are better positioned than LNG, but there are still plenty of factors and investigation needed to form meaningful conclusions that can be applied to the maritime industry. This report looked at the supply side aspect in new-technologies, however, more information should be developed with respect to ship combustion technologies, processing techniques/infrastructure and scientific know-how as these are some of the largest concerns outside the scope of this study.

Preface

In these past nine months, I have had the great pleasure and opportunity of conducting my master thesis under the guidance and supervision of a remarkable group of people. I would like to start off this thesis by acknowledging everyone that was part of it and the people that helped me reach my goal. First and foremost, Jeroen Pruyn, thank you for the support, guidance and advice you have given me throughout the project. However, I am most grateful for your patience with me and your adaptability, which has allowed me to carve my own way through the project. Thank you for being understanding and allowing me to learn in the right way. Next, Pieter 't Hart, it was always interesting hearing your thoughts and opinions throughout the project. Thank you for your sincere interest in the study and all of your suggestions. I would like to also thank all of the representatives from Goodfuels that have been involved in this work; Olivia Morales, Felipe Ferrari, Bart Helllings and Rianne de Vries for their input and help at the first stages of the project. Additionally, a special thanks to Felipe and Olivia for their help with some additional questions. I appreciate you both taking time to help me with some of my concerns to which your input was very helpful. It was an honor to work with each and every one of you, and can genuinely say I have learned something from each person.

Throughout the project, I was forced to brush up on a lot of skills I had not used in a while. Though I have gained enormous knowledge on the subjects of this work, in particular Python, it would have not been possible without Eric Dedding and Mohammed Khalifa. Thank you for the help and for putting up with the random questions I asked form time to time.

Delft, November 8 2020

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Nomenclature

CO_2	Carbon Dioxide
NO_x	Nitrogen Oxides
SO_x	Sulfur Oxides
API	Application Programming Interface
BSC	Biofuel Supply Chain
EAFO	European Alternative Fuels Observatory
ECA	Emission Control Area
EGR	Exhaust Gas Recirculation
EIA	Energy Information Administration
GHG	Green House Gasses
GIS	Geographic Information System
IEA	International Energy Agency
IFO	Intermediate Fuel Oil
ILUC	Indirect Land Use Change
IMF	International Monetary Fund
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
MARPOL	International Convention on the Prevention of Pollution from Ships
MC	Moisture Content
MDO	Marine Diesel Oil
MGO	Marine Gasoil
MILP	Mixed Integer Linear Programming
MKC	Maritime Knowledge Center
MSW	Municipal Solid Waste
OPEC	Oil Producing and Exporting Countries
PM	Particulate Matter
RED II	Renewable Energy Directive II
SCR	Selective Catalytic Reduction
SEC	Specific Energy Consumption
TRL	Technology Readiness Level

UAA	Utilized Agricultural Area
ULSFO	Ultra Low Sulfur Fuel Oil
UN	United Nations
VLSFO	Very Low Sulfur Fuel Oil
WEO	World Economic Outlook

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Introduction

To date, fossil fuels account for the primary source of the world's energy consumption. The reliance on these fuels has not only caused multiple deleterious effects on the environment, the planet and human kind, but the high consumption of these resources will soon lead to their total depletion, making them unsustainable. Decision makers worldwide are searching for alternative energy sources for future consumption. According to the World Economic Outlook (WEO) from the International Monetary Fund (IMF), forecasts predict that the supply of fossil fuels will be depleted in the next 50 years [16]. As a result, many governments have made it a priority to move away from fossil fuels and switch over to cleaner forms of energy. Industries that have traditionally relied on oil are gradually shifting away from it. The shipping sector is no exception, as it accounts for 2.5% of global greenhouse gas emissions (940 million tons of CO_2), 4-9% of SO_x, and 10-15% of NO_x annually [17]. These figures are projected to increase in a business-as-usual scenario which is why regulating bodies have begun imposing stricter guidelines.

In particular, the last couple of years have seen increasingly rigid measures regarding emissions in the shipping industry. The International Maritime Organization (IMO) has made it its goal to reduce fleet CO_2 emissions by 30% by 2030 and 50% of total GHG fleet emissions by 2050 (compared to 2008 levels). Depending on the growth of the worldwide fleet, the latter will mean that for each ship, around 70-85% GHG emissions will have to be reduced. Additional regulations have been imposed pertaining to sulphur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter (PM) emissions. This means that any decarbonisation efforts also have to comply with non-GHG emission reductions. It is clear that if the shipping industry is to survive in this evolving world, it must also be transformed to keep up with the needs of a green planet.

There are various potential ways of achieving these GHG cuts and many have been implemented in the past with ambitions of emission reduction and fuel savings. The two main approaches to GHG reductions in ships include being more energy efficient (i.e. increasing ship efficiency, improved hydrodynamics, reducing fuel consumption through more efficient engines, lower onboard energy consumption, etc.) or using a different energy carrier/fuel with lower life-cycle GHG emissions. This study focuses on the latter of the two options; the use of alternative fuels.

In the long term outlook (2050 onward), it is expected that the energy carriers onboard ships will gradually shift towards hydrogen fuels and electric batteries [18]. These energies outperform current energy sources in almost every aspect related to renewability and with the right infrastructure can be fully sustainable with nearly zero emissions [19, 20]. However, the technologies required for the implementation of such systems are still a long ways of being developed. That is why ship-owners and fuel companies are looking elsewhere to find intermediary fuel options for the first phase of the energy transition (2025-2030). Choosing the wrong solution can lead to serious competitive disadvantages for fuel companies and ship-owners. It is therefore important to analyze all options and plan with flexibility in mind. Low carbon fuels including biofuels are an interesting option to achieve these goals while still being attainable within a five-year period. The drop-in nature of many of these fuels makes them an attractive choice since they can gradually be added and mixed with prevailing fuels and require little to no infrastructure changes to ship's engines. A study carried out by shipping line A. P. Moller – Maersk and classification society Lloyds Register said that based on market projections, the best positioned fuels for research and development into net zero emissions for shipping include alcohols (ethanol and methanol) and biomethane [21].

European shipping giant Maersk has taken a large step towards the use of these fuels itself. Early in 2021, Maersk announced plans to unveil the world's first carbon-neutral cargo vessel by 2023, seven years ahead of schedule. In a press release, the company stated that the methanol-fuelled ship would be introduced early due to increasing demand from customers [22]. On top of this, Maersk plans on installing dual fuel technology on all future newbuilds to allow for carbon neutral operations or operations on very low sulphur fuel [22]. Critics of this decision have pointed to the fact that methanol may not be sustainable and available in sufficient amounts. The company has admitted that indeed, the biggest challenge may be in finding sufficient supplies of carbon-neutral methanol to supply the ship. This is a concern shared by many stakeholders in the maritime industry. A report launched at the 2019 UN Climate Change Conference highlighted the fact that "There remains no clear consensus on whether there is sufficient sustainable biomass for shipping as well as other sectors" and that "current understanding suggests that a biomass-based decarbonization pathway for shipping comes with considerable supply risks and as a consequence also poses risks related to their price" [23]. However, many experts believe that biofuels could meet 10-30% of shipping's energy needs by 2030, and have suggested that while biofuels might not be a long-term solution, they could significantly accelerate decarbonization in the short term [24].

The environmental impact of fuel is not limited to the emissions released in the combustion of the engine, but also the entire fuel life cycle including the supply chain (cultivation, refining, distribution etc.). The challenge with biofuels is therefore creating cost effective supply-chains that are able to meet market demands while still managing to reduce life-cycle emissions compared to other traditional fuel options.

1.1. Background Information

Though a relatively established concept, energy from biofuels and biomass has seen a sharp rise in interest particularly in the last 10 years. From heating to electricity to the automotive sector, the use of biomass/biofuels and the infrastructure for them is steadily growing. Until now, the focus has mainly been on large scale production of fuels such as ethanol in automotives and bio-diesel in marine vessels. These fuels can be produced at relatively high outputs and are derived from first generation biomass sources. Recently, however, this trend has shifted and the focus is now on utilizing lignocellulosic biomass and non-crop products for biofuel production purposes. The shift to these non-food sources includes food and energy security considerations. The technologies and infrastructure for second generation biofuels are still in the development phase because the economical and logistical aspects are still not well documented.

In 2020, an exploratory study entitled "The potential of drop-in biofuels for the maritime industry" by D. van der Kroft looked into the potential of drop-in bio-diesel for the shipping industry [25]. The study modeled the worldwide supply-chain of several oil-based bio-fuels. The results of the research determined the optimal placement of refinery hubs and feedstock locations across the globe for the production and distribution of these biofuels. Key however, were findings on cost, availability and CO_2 reduction potential. Van der Kroft specifically investigated oil based fuels because the feedstocks for those are commercially available and the required infrastructure for the production and processing exists. A main drawback of using those fuels however, is that some of the main feedstocks compete directly with the food industry and cause indirect land use change (see section 1.3).

This thesis builds on Kroft's developments and looks into the supply-chains of advanced, non-oil-based biofuels, namely bio-LNG, bio-ethanol and bio-methanol in Europe. These fuels can be made from a range of feedstocks derived from agricultural byproduct and solid wastes, which allows for production to be more localized, less harmful to the environment, and in less competition with the food industry.

Bio-methanol, along with bio-ethanol and bio-LNG are potential fuels with low carbon, nitrogen and sulfur emissions that can be derived from plant and waste sources. Though they outperform traditional oil based fuels in terms of life-cycle emissions, they are not highly utilized in the industry. (Bio) Ethanol or methanol powered engines are virtually nonexistent in large transport vessels, while bio-LNG/LNG-vessels make up a small but considerable portion of the maritime fleet. The chemical properties of these fuels make it challenging to switch over to them and would require large investment costs for retrofitting existing ship engines. Moreover, there are many concerns regarding the supply and availability of these fuels. Even if vessels were able to economically switch to these engines, would there even be enough supply of fuels and availability of feedstock to meet the demand?

1.2. Why Now?

The recent 2020 regulations on sulphur, nitrogen oxides and particulate matter have spiked interests in biofuels. From now on, marine fuels and engine technologies will need to be low in sulphur, nitrogen and particle emissions. For biofuels, critical considerations for selection will pertain to the sustainability of the feedstock, including issues on land use and ecological footprint, cost and availability. More emphasis is being placed on second-generation biofuels, as these are less ecologically damaging and can be produced more locally, which can lead to faster commercialisation. The economies of scale involved in worldwide production and distribution of biofuels are far from being realistically implemented due to unequal distribution of technologies/infrastructure and lack of (cohesive) international incentive. Localized production is currently more favorable and could be achievable in the EU.

It is widely known that the EU's energy policies head towards the development of renewable energies, seeking to reach energy sustainability by reducing international energy dependence [26]. Though many countries are part of a gobal/collective effort to combat climate change, the majority of binding policies relating to energy supply and demand are set and enforced at a national level resulting in a divergence between the scope and policy ambitions of separate countries. An economically efficient development of sustainable energy cannot be achieved by Member states alone. The European Union has the necessary policies, funds, cooperation and ambitions to become one of the first areas globally to embark on the journey to the large-scale development of biofuels. Moreover, a coordinated approach avoids fragmentation of goals and is more efficient by fully exploiting economies of scale and technological cooperation. While all EU countries have domestic renewable energy resources to exploit, some areas of Europe have a greater potential for renewables than others. For instance, some countries may have more forests suitable for wood based feedstocks, while others may have more livestock or agriculture, and thus be better suited to produce agricultural bi-products.

One of the major challenges in predicting the viability of biofuels as an alternative fuel source is being able to accurately model the future demand of these fuels. In order to model future demand, it is useful to have a clear understanding of the current and past demand patterns. Until now, predictions of future fuel demand were only marginally accurate. However, early in 2021, the MRV made emission data on ships in European water publicly available for the first time. The publication of this information has led to insight into marine fuel demand and bunker behaviour. The market responses to the new regulations are also now apparent. This has allowed for more complete fuel demand models to be formed, which previously did not have this level of detail.

The three biofuels considered in this study can be processed from second generation biomass sources, which are available in large quantities and in diverse geographies. The feedstock used for their production have little to no sulfur content and are compliant with environmental emission regulations. Although the infrastructure for ethanol and methanol vessels is almost nonexistent, the current development of multi-fuel engines is paving the path for future marine engines which will allow for the use of oil, gas, as well as alcohols (e.g. methanol or ethanol) in a diesel cycle [27]. This might see the increase of ethanol and methanol in the maritime fleet in the medium to long term.

The aim of this project is to use the available data to provide insight into which bio-raw materials are suitable for the production of these three fuels in the first phase of the energy transition (2025-2030). More specifically, to what extent will these fuels be able to meet the demand in Europe.

1.3. Biofuels

Biofuels are fuels that are produced from materials deriving from plants or animals, referred to as biomass. Though many types of biomass can be directly used as fuel, in order to create biofuels, biomass usually has to go through several processes to turn the raw materials specifically into a liquid or gas.

The reasons for the production of biofuels as opposed to traditional petroleum based fuels include energy security reasons, foreign exchange savings, socioeconomic issues, but mainly environmental concerns [28]. The cultivation, processing, transportation and combustion of biofuels emit less CO_2 equivalent emissions than traditional fossil fuels. Moreover, since many biofuels originate from plant sources, they absorb atmospheric CO_2 during their cultivation [29]. There is also evidence that biofuels presently have the highest emission reduction potential compared to other proposed methods (such as hull design, power and propulsion systems, alternative power sources and operational methods) [30].

Biofuels can be classified into first, second, third and fourth generation depending on the originating biomass. A visual representation of this along with some examples can be seen in figure 1.1.

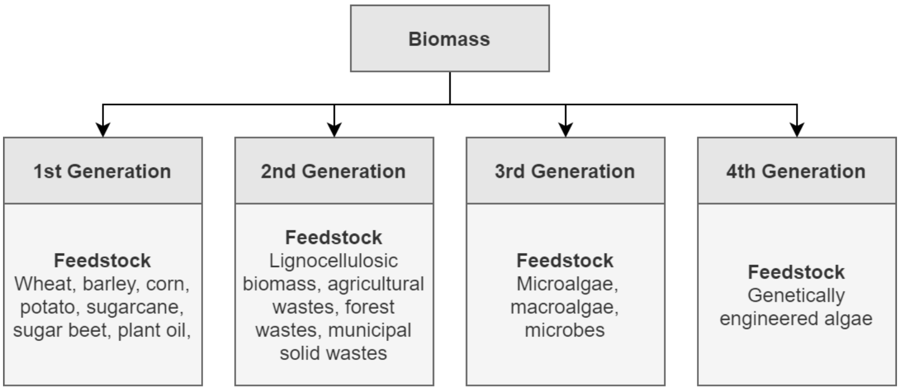


Figure 1.1: A breakdown of feedstocks of the different generation biofuels, adapted from [1]

In other terms, first generation biofuels are derived mostly from edible crops, second generation derive from byproducts of plants/crops and animals, third and fourth generation come from different algae. Lignocellulosic feedstocks can include a mix of purposely grown energy crops, byproducts, or agricultural residues (wheat straw, corn stover etc.) plus the biogenic component of municipal solid waste. These materials are usually harder to convert into fuels due to the fact that their energy content is harder to access than the starchy and fatty content in first generation feedstock.[22]

One of the main distinctions between first and second generation biomass is that second generation feedstock does not directly compete with the food industry. Since land is a limited natural resource, there is competition between the sectors that use it. The primary land demand falls into either food production (livestock and crops) or wood logging (firewood and industrial roundwood). First generation energy crops compete directly with food production whereas second generation are generated as a bi-product of food and wood. As a result of being crops, first generation feedstock are also subject to seasonal and regional availability. On the other hand, second generation biomass can be produced in geographies unsuitable for farming or in urban locations (i.e. from municipal wastes).

Algae and other third generation feedstock seem promising, as they don't compete with land use, but the current status does not make them suitable for the adoption in 2025-2030 [27, 31].

The production of biofuels can have harmful effects on the environment, and this is especially true of crop-based fuels. Certain crops can cause indirect land use change (ILUC) whereby increasing demand causes land expansion and deforestation leading to increased emissions. However, these effects are highest for oil crop-based biofuels and the impacts from sugar and starch based alcohols are small [32]. ILUC effects are generally negligable for second generation feedstocks as these are generated as biproducts of crops.

The specific fuels studied in this report originate only from second generation biomass. Sections 5.1.1-5.1.3 take a closer look at them.

1.4. Shipping Emission Regulation

Since shipping is an international industry that operates across many countries, emissions are mainly regulated by a subsidiary agency of the UN, namely, the IMO. Since 1997, the IMO has been releasing regulations pertaining the pollution of air from ships. Currently, these regulations are contained in the "International Convention on the Prevention of Pollution from Ships" (MARPOL) and set limits on the levels of CO_2 as well as NO_x and SO_x.

The NO_x emission standards are listed in Annex IV of the RED II and set certain limits on the NO_x particle expulsion depending on the engine rpm. Tier I and II pertain to ships built on or after 2000 and 2011 respectively and have to be complied with globally. Tier III concerns ships built on or after 2016 and only applies in Emission Control Areas (ECAs), which are highlighted in figure 1.2. The areas highlighted in dark blue represent the ECAs. As can be seen, they're mainly located in northern Europe and coastal United States. These NO_x standards can be upheld by altering the combustion process to change the byproducts of engines (for example, combustion temperature).

Annex VI also includes caps on sulfur content of fuel oil to control SO_x emissions, and indirectly, PM emissions. The current sulfur limit in fuel is 0.5% globally, and 0.1% in ECAs.

Apart from the IMO, the EU has also set guidelines and a strategy to reduce shipping emissions. The EU's strategy consists of three consecutive steps:

1. Monitoring, reporting and verificatiion of CO_2 emissions from large ships using EU ports.
2. Greenhouse gas reduction targets for the maritime transport sector.
3. Further measures, including market-based measures in the medium to long term.

With respect to the first point, companies are required to monitor the emissions and fuel consumptions (along with other parameters) and report them to the MRV. The first and second points are made to gauge what is realistically achievable in terms of emission reductions. The final point highlights the fact that more and increasingly rigid measures will be passed in the medium to long term. Knowing this is the case, ship owners should account for probable future regulations/scenarios and plan accordingly.

Source: IFPEN

Figure 1.2: Current and potential global emission control areas [2]

Next to low-sulfur fuels, scrubbers represent one of the most common methods for the compliance to SO_x limits. Compared to engine retrofitting (for alternative fuel use), scrubbers are relatively easy to install. However, the downside with scrubbers is that they increase the fuel use of the engine and therefore also increase GHG emissions [33]. Other technologies such as Exhaust Gas Recirculation (EGR) or Selective Catalytic Reduction (SCR) to comply with NO_x emission regulations have the same undesired effect. Therefore, the most suitable option for decreasing emissions in the short to medium term are biofuels, which reduce supply-chain emissions while complying with sulfur regulations.

1.5. Reader's Guide

This paper is organized as follows. Chapter 2 describes the problem in detail and formulates the method and scope to develop a solution. Chapter 3 presents a comprehensive literature review with regard to biofuel supply chains, along with a critical review of optimization techniques and developments. The supply of biofuels across the EU is presented in Chapter 4, while Chapter 5 focuses on the demand. In Chapter 6, the mathematical model is formulated and displayed. Chapter 7 delves deeper into the techno-economic parameters used to describe the model. The verification and validation of the model are perforemed in Chapter 8 and the different scenarios are presented in 9. Finally, an in-depth discussion of the research is completed in Chapter 10, and the conclusions follow in the final and last chapter.

2

Problem Statement

The following chapter explores the problem in more depth and provides additional information on current biofuel use and the challenges involved in switching to alternative biofuels. Further, the scope, methodology and problem description are presented in a comprehensive manner to outline the problem in greater detail and establish the bounds and foci of this study.

2.1. Current and Potential Use of Biofuels in Shipping

The three outlined fuels; bio-ethanol, bio-methanol and bio-LNG are not highly utilized as ship fuel. This is especially true of the alcohols. In this paper, only a few projects that used methanol as a marine fuel were identified and no projects using ethyl alcohol were found. The lack of ethanol projects can be attributed to the historically higher price of ethanol compared to methanol [34], however, the same might not be true of their bio counterparts. Further, methanol has gotten a bad name due to its toxicity risks when consumed and safety issues concerning its invisible flame [35]. Their potential has therefore not been fully studied nor demonstrated, though it is clear that they do offer many benefits in terms of emissions compared to current-use fossil and bio fuels.

As of today, the most widely used fuels for maritime are HFO followed by MDO and LNG. There are also certain low-sulfur fuels such as VLSFO and ULSFO that comply with ECA regulations, but these come at the cost of increased prices through extra refining and consequently, higher CO_2 emissions. Since LNG-powered engines exist on a small portion of the fleet, the change to bio-LNG would be relatively simple for these vessels as it does not require any engine retrofitting or new installments (on the ship itself). The inland shipping branch has shown interest in using bio-LNG as a shipping fuel, and a few ships are already operational [36]. So if the bio version of LNG was price competitive, this would garner large interest.

Insofar as biofuels, present use is centered around oily, drop-in fuels such as biodiesel and hydrotreated vegetable oil. However, in the European Union, the Renewable Energy Directive (RED) II has classified palm oil-based biodiesel under a high ILUC risk category [37]. As a result, biodiesel consumption in the European Union is expected to fall below current levels.

Apart from availability concerns, some of the reasons as to why ethanol and methanol have not gained traction in the maritime industry include; chemical/physical properties of these two fuels, and lack of cost and economic data. Specific chemical properties such as low flash point and low energy density make these alcohols difficult to work with. These properties translate into issues concerning vessel range, fuel storage and additional safety requirements. For these reasons and more, very few operational shipping vessels can run on ethanol or methanol. If this were to change in the near future, compatible engines would have to be installed on newbuilds or retrofitted onto existing vessels.

There are only about nine methanol ships on the water today. Though compatibility with current use engines and vessels is definitely an issue, "the main challenge is not at sea but on land," as Søren Toft, Maersk Chief Operating Officer puts it. The technological changes inside of the vessel are minor when compared to the solutions needed for the production and distribution of these energy sources on a large/global scale.

This uncertainty, tied into the fuel demand in Europe leads to the main research question of the report:

Table 2.1: Chemical and physical properties of the different fuels.

Properties	HFO	MGO	LNG	Methanol	Ethanol	Biodiesel
Physical State	Liquid	Liquid	Cryogenic Liquid	Liquid	Liquid	Liquid
Boiling Temp. at 1 bar [C]	-	175-650	-161	65	78	315-350
LHV [MJ/kg]	40	43	50 (-163 C, 1 bar)	20	28	43
Flash Point	60	60	-175	12	17	100
Auto Ignition Temp. [C]	-	250-500	540	464	363	750
Max Sulfur Content (%)	3.5	1.5	0.06	0	0.01	0.0015

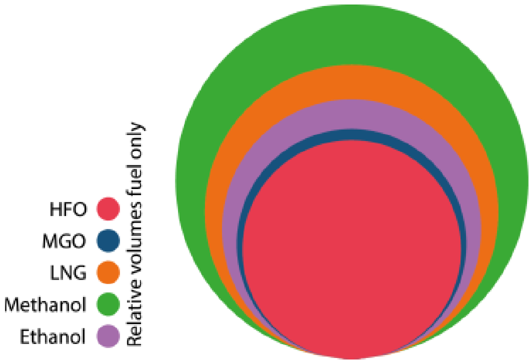


Figure 2.1: Relative volume of fuels for the same energy [3].

Which are the most suited bio-raw materials for the production of bio-LNG, bio-ethanol and bio-methanol in Europe for the first phase of the energy transition (2025-2030)?

In other words, to what extent will EU biofuel production be able to meet the projected demand of these three biofuels from European ports. On top of that, which feedstock/bio-raw material will be best suited for the productions of these fuels. This information will be useful for future investments regarding biofuel production infrastructure. Suitability of a feedstock is determined on the basis of availability, cost and life-cycle emissions. These three factors are some of the most important determinants in predicting a fuel's future success.

2.2. Supply Challenges

The total costs and emissions can only be accurately quantified when a complete life-cycle analysis (LCA) is carried out. The process of creating the fuel must be studied from well-to-tank to account for costs and emissions at all stages. For this, it is essential to understand the separate stages and most important factors involved in the production process. Only when this is done can the supply chain of the fuels be modelled and optimized for a certain objective(s). This introduces the first sub-question:

How can biofuel supply chains be accurately represented and modelled?

Answering this question entails carrying out a literature study on biofuel supply chains. Aside from understanding how to model them, it should also be know what factors to include in the modelling. As stated earlier, much of the infrastructure to produce these three fuels (from second generation sources) is still lacking. Certain assumptions will have to be made with respect to the current and future fuel-producing capabilities of each country. A simple but robust approach for assessment of biomass supply potentials is to look at the production from current agriculture, forestry and waste. In other words, determine what can be achieved by adapting the agricultural crops and technologies without compromising food production or increasing land use.

Technical availability is not the only obstacle in the supply chain. Before availability becomes a limiting factor, the production capabilities of biofuel refineries should be addressed. The different technologies required to convert these fuels are at different maturities with many still in their infancy. The processing facilities are unevenly distributed across European countries, leaving some better prepared than others. On top of this, the supply of the produced biofuels as well as the biomass will face competition from different industries.

It will be interesting to see whether the supply of biofuels in the EU will be able to match the demand in the time period in question. The focus is on the use of domestic (insofar as the in-scope countries) biomass resources for biofuel production. However, international trades of biomass/biofuels may also provide win–win opportunities to both exporting and importing countries through economies of scale. The hypothesis is that, with second generation feedstock, the price and logistics of localized production will outweigh some of the benefits of economies of scale. Regardless of whether this is the case or not, it is most important to find which of the available resources (biomass) are most suitable to produce these fuels in the present/near future. With that in mind, the second sub-question can be posed as:

What are the production capabilities (for biofuels) of each considered country?

Of course, to model the distribution of the fuels across the countries in consideration, it should be know what the transportation options for this are and how it can be achieved. This leads to the third question:

What are the available and preferred trade routes inland and at sea for the transport of feedstock and fuel.

2.3. Demand Challenges

Demand for biofuels is the key determinant in driving the whole initiative towards these alternative fuels. The demand however, depends on a multitude of factors including regulations, costs, availability, sustainability, economic level, incumbent technology, etc. It is therefore difficult to model future demand scenarios for specific fuels with high accuracy. However, it is possible to model future scenarios by identifying trends in current and past data for fuel use in general. This can be achieved by studying the bunkering behavior of ships, thus, another key question is:

What is the bunker behavior of ships in European ports and how can this be used to model future worldwide biofuel supply and demand?

The demand for marine fuel is set to increase in following years in line with seaborne trade and and global GDP [38]. Regulations will be the main driver behind the push towards cleaner fuels [38]. Future GHG limits combined with current environmental policies will create a demand for biofuels as a replacement for fossil fuels. In other words, biofuels will be attractive in markets where fuel costs are low compared to total operational costs and green systems are seen as marketable assets. To capture these distinct possibilities, different demand scenarios will be created.

2.4. Costs

"The Commission should focus the allocation of funds on the reduction of the cost of capital of renewable energy projects since such cost has a material impact on the cost of renewable energy projects and on their competitiveness, as well as on the development of essential infrastructure for an enhanced technically feasible and economically affordable uptake of renewable energy" - RED II [39]. The cost of biofuels is higher than the cost of fossil fuels and is expected to remain so in the short to medium term [40]. The willingness of shipowners to make the switch to biofuels will largely depend on the cost differential between these and other available options. Concievably, specific mandates on biofuels or carbon taxes may make biofuels economically more competitive in the near future. Regardless, the selling price of biofuels is still tied to the price of oil since up to 50% of operational expenses are chiefly dominated by fuel costs. On top of the fuel costs, the majority of ships running on these new fuels will have to either be retrofitted or newly-built to acommodate these new fuels. So, additional to the variable fuel prices, ship-owners will also be faced with large fixed costs.

Shipowners will have the choice to opt for other options such as using low sulfur fuels (LSF) or installing onboard scrubbers. The willingness of vessel owners to install these new systems onboard their vessels will depend on the cost differential between these fuels and other options. Onboard scrubbers (as an alternative to low carbon fuels) usually require investment costs of $3-5M and are associated with a 2-10 year payback period [41]. However, the majority of scrubbers being installed have open-loop systems that discharge the accumulated sulfur into the ocean. These systems are not allowed in ECAs. For a comparison to be made, the following question must be answered:

What are the costs involved in the production and distribution of the outlined biofuels?

An important objective of the biofuel supply chain will therefore be to produce biofuel products in an economically viable manner. Some of the most chosen economic criteria in BSC are maximizing the net present value or total annualized cost. Both metrics account for the time value of money by using a discounted cash flow analysis.

2.5. Sustainability

"When developing support schemes for renewable sources of energy, Member States should consider the available sustainable supply of biomass and take due account of the principles of the circular economy and of the waste hierarchy established in Directive 2008/98/EC of the European Parliament and of the Council in order to avoid unnecessary distortions of raw materials markets. Waste prevention and recycling of waste should be the priority option. Member States should avoid creating support schemes which would be counter to targets on treatment of waste and which would lead to the inefficient use of recyclable waste." - (RED II), Binding overall Union target for 2030.

Sustainability can be defined within environmental, social and economic frameworks. These frameworks are connected, and often require a trade-off. However, in the context of this study, sustainability will be centered around the environmental framework. The report will cover climate change through quantifiable emission calculations. Environmental effects from both the production as well as use of fuels are important. Effects should be considered both from the perspective of existing regulations but also possible future regulations. The Renewable Energy Directives I/II contain a list of feedstocks that receive special treatment for the purposes of the RED II transport target. According to this directive, advanced biofuels are defined as liquid or gaseous biofuels made from list A in Annex IX. They have a specific sub-targets starting at 0.2% in 2022, minimum 1% in 2025 and at least 3.5% by 2030 for the entire transport sector [42]. (it is assumed each industry within the sector has a responsibility of meeting those figures, i.e. the maritime sector will strive to reach these targets independently of other industries in the transport sector)

To accurately capture and quantify the sustainability, a Life Cycle Assessment will be implemented. According to ISO standards, an LCA has four stages: goal and scope definition, project description, goal of study, boundary of system, and definition of functional unit. The cradle-to-grave life cycle boundary is often adopted in BSC modeling and optimization, that allows for the comparison between biofuel products and their petroleum counterparts throughout the entire life-cycle. However, this report will do an LCA on the supply chain up to the point where the fuel is bunkered, in other words, a cradle-to-tank analysis. The combustion and engine performance of the fuels are beyond the scope of the project.

To compare various biofuel products in a BSC, units are expressed in energy content (eg, gasoline equivalent gallon or jules) which serves as the basis for calculation. The first phase of the analysis; the inventory analysis, involves the compilation and quantification of life cycle inventory (LCI) associated with each component within the life cycle boundary, which is a comprehensive list of materials consumed and emitted in the process. This can include the costs and emissions. In the impact assessment phase, the LCI is translated according to the chosen damage assessment model that generates a weighted score or a series of numeric indicators of environmental performances, which can be easily understood by the users. In the final phase of interpretation, the LCA results are analyzed to provide a set of conclusions and recommendations. To do this, the following question should be answered:

What are the lifecycle emissions of the considered biofuels?

Regarding the LCA rules, the directive states that wastes and residues "shall be considered to have zero life-cycle greenhouse gas emissions up to the process of collection of those materials" since their generation is usually not the intended product of a production system. Therefore, any emissions/costs due to the "production" of the feedstocks will not be considered as part of the LCA. Further, these fuels need to meet the same minimum GHG emissions savings as all biofuels, which range from 50-65% depending on the start date of the installation &Environment2020[&Environment2020]. This includes only direct emissions. Direct emissions are owned and controlled by the reporting entity as opposed to indirect emissions which are from sources that are not owned and not directly controlled by the reporting company though add to the carbon footprint (i.e. as a result of the generation of purchased electricity, fuel, and other services) [44].

2.6. Research Questions

Following from the introduction and the preceding sections, the higher level objective of this research is clear; gaining an insight on the supply and demand scenarios of three types of biofuels for the maritime industry and the costs and emissions associated with those. To answer the uncertainties posed in the sections above, a main research question is formulated.

Which are the most suited bio-raw materials and sources for the production of bio-LNG, bio-ethanol and bio-methanol in Europe for the first phase of the energy transition (2025-2030)?

Sub-questions

i ***How can biofuel supply chains be accurately represented and modelled?***

ii ***What are the production capabilities (for biofuels) of each considered country?***

iii ***What are the available and preferred trade routes inland and at sea for the transport of feedstock and fuel.***

iv ***What is the bunker behavior of ships in European ports and how can this be used to model future worldwide biofuel supply and demand?***

v ***What are the costs involved in the production and distribution of the outlined biofuels?***

vi ***What are the lifecycle emissions of the considered biofuels?***

vii ***How do these feedstock and supply chains compare to the existing feedstock and supply chains for biodiesel?***

The last subquestion is included not necessarily as part of the research, but as a comparison of the research to other alternatives. This serves to put the results into perspective and as further aid to decision-making.

2.7. Scope and Methodology

This study aims to determine the viability of certain fuels in Europe for the marine industry. The conclusions derived from this report may be of use to establish the greater production capability of biofuels in Europe for maritime (and other applications).

The scope of the study however, is limited to certain countries, feedstocks, ports and timeframe. All feedstocks considered are included in Annex IX of RED II. A complete and detailed list of these biomass sources can be found in table 6.3. The study will be carried out in anticipation for the period 2025-2030. Current and past data/trends will be used to form predictions on future scenarios. Further, the countries considered in this study are the European member states plus the UK, Norway and Switzerland. Small countries as Cyprus, Luxembourg and Malta are not considered in the analysis, as these are not significant producers of biomass or fuels. The choice to include/exclude certain countries was mainly done based on data availability. Data on the listed countries is readily available from verified sources and on multiple themes. The full list of countries is given below in a table and highlighted on a map.

1. Austria	8. Finland	15. Latvia	22. Slovakia
2. Belgium	9. France	16. Lithuania	23. Slovenia
3. Bulgaria	10. Germany	17. Netherlands	24. Spain
4. Croatia	11. Greece	18. Norway	25. Sweden
5. Czechia	12. Hungary	19. Poland	26. Switzerland
6. Denmark	13. Italy	20. Portugal	27. United Kingdom
7. Estonia	14. Ireland	21. Romania	

The European ports considered are listed below. These are some of the busiest and most frequented ports across the EU. For a few, port specific bunkering data is available from the respective official port website.
Due to the scope and considerations of the report, the potential of the biofuels will be assessed on the theoretical, technical and economic levels. On the highest level, the maximum amount of biomass which can be considered theoretically available within bio-physical limits will be considered. In terms of waste biomass,

Figure 2.2: Map of the in-scope European countries.

1. Antwerp, Belgium	6. Genoa, Italy	11. Algeciras, Spain
2. Le Havre, France	7. Gioia Tauro, Italy	12. Barcelona, Spain
3. Bremmerhaven, Germany	8. Rotterdam, Netherlands	13. Valencia, Spain
4. Hamburg, Germany	9. Gdansk, Poland	14. Felixstowe, United Kingdom
5. Athens, Greece	10. Sines, Portugal	15. Southampton, United Kingdom

the theoretical potential is equivalent to the total amount that is produced. Once this has been achieved, a techno-structural framework will be applied, which will set various constraints with respect to the limitations of technology and infrastructure. An economic set of inputs such as costs, competition and sustainability will bring out a more realistic, economic potential of producing these fuels through the proposed supply chains. Further, the economic analysis will depend on the demand of each biofuel. This will not only show the economic profitability of the system within the given framework, but create a dependence link between the supply and demand frameworks. Lastly, the implementation potential is the portion of the economic potential that can be achieved within a certain time span and under particular socio-political framework conditions, including economic circumstances, social constraints and policy changes. To account for this, multiple scenarios will be made for various future possibilities.

Sustainable implementation can generally be thought of as being a ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’. As explained, the concept of sustainability is commonly defined within ecological, social and economic contexts. The three pillars are connected via feedback mechanisms, trade-offs and synergies. Because of the large range of aspects, it is difficult to assess a single ’sustainable bioenergy potential’. However, since the production and use of biomass for bioenergy purposes affects all dimensions of sustainability, there is a strong demand for inclusion of sustainability aspects in assessments of the different bioenergy potentials. Therefore, the sustainability implementation potential will be looked into with a focus on the environmental aspect. The only consideration in evironmental will be climate change in terms of emissions (biodiversity, water quality/quantity, air quality, etc. will not be evaluated). The social and economic aspects will be included, but in less detail.

The investigation will be carried out in five main steps described by Figure 2.4. In each step, considerations will be taken to assess and quantify the five sustainability criteria/potentials.

Though both the demand and supply of biofuels will be studied, the general approach to the biomass resource assessment will be supply focused as opposed to demand driven. Within this approach, a statistical method will be applied that makes use of publicly available data and literature (e.g. land use, crop yields, crop production, etc.). The collected data will then be combined with conversion factors such as yields, residue to crop factors, etc. In addition, further assumptions are made on the fraction of biomass available for maritime fuel production, taking into account biomass needed for other industries and purposes.

Due to the time requirements and purpose of the research, the degree of detail and accuracy will be basic.

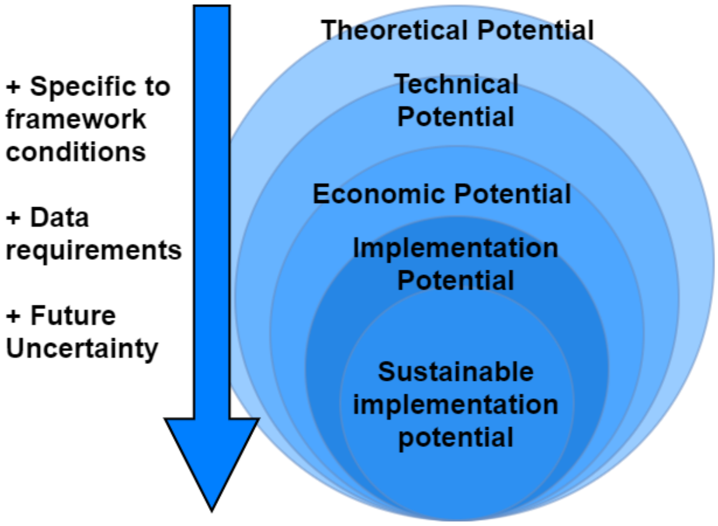
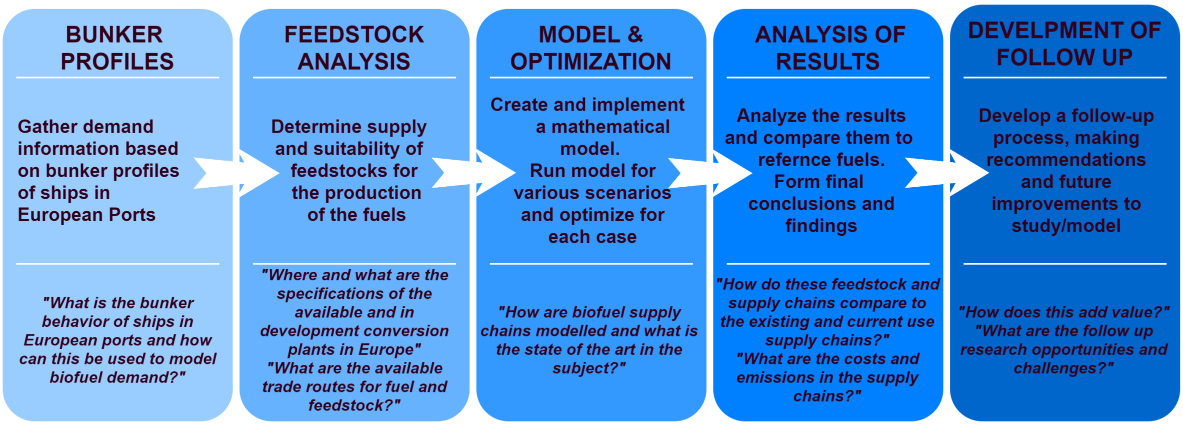


Figure 2.3: Different levels of biomass potentials (adapted from [4]).



BUNKER PROFILES

Gather demand information based on bunker profiles of ships in European Ports

"What is the bunker behavior of ships in European ports and how can this be used to model biofuel demand?"

FEEDSTOCK ANALYSIS

Determine supply and suitability of feedstocks for the production of the fuels

"Where and what are the specifications of the available and in development conversion plants in Europe"
"What are the available trade routes for fuel and feedstock?"

MODEL & OPTIMIZATION

Create and implement a mathematical model. Run model for various scenarios and optimize for each case

"How are biofuel supply chains modelled and what is the state of the art in the subject?"

ANALYSIS OF RESULTS

Analyze the results and compare them to refernce fuels. Form final conclusions and findings

"How do these feedstock and supply chains compare to the existing and current use supply chains?"
"What are the costs and emissions in the supply chains?"

DEVELPMENT OF FOLLOW UP

Develop a follow-up process, making recommendations and future improvements to study/model

"How does this add value?"
"What are the follow up research opportunities and challenges?"

Figure 2.4: Caption

What this means is that the data sources used will be ones that are public and easily accessible, and the analysis will be done for a larger region while partially compromising on detail.
A more detailed list of the process is presented below:

1. Desk study to draw up bunker profiles for a large number of European ports (regarding sustainable biofuels such as bio LNG, bio Methanol and bio Ethanol).
    (a) Gather data on specific port consumption and energy use for the maritime sector across Europe.
    (b) Use data to model current and future supply and demand of these three biofuels.
    (c) Create multiple future demand scenarios using the gathered data or through other sources.
2. An analysis of feedstock suitable for conversion to sustainable Bio-LNG, Bio-Methanol and Bio-Ethanol biofuels for shipping. The focus is on use of large volume residual flows from agriculture and forestry, for example the raw materials from Annex IX list A from RED 2.
    (a) Research into each separate biofuel and the production processes.
    (b) Determine locations of each production facility, costs, and potential outputs (supply).
    (c) Determine any other factors that might be of interest/value for each production facility.
3. An optimization of the available feedstocks, production, transport and available ports, both in terms of emissions and costs.

   (a) Create mathematical model.
   (b) Program the model and run multiple scenarios.
   (c) Verification and Validation of the model.

4. Comparison of the suitability of the biofuels of bio-LNG, bio-methanol and bio-ethanol with that of biodiesel based on residual flows from agriculture and forestry. Based on the following criteria: availability (scalability) and costs for the maritime sector
   (a) Gather information on biodiesel supply chains.
   (b) Run the model for biodiesel and see how that compares to the other fuels and previous literature.
5. Development of a follow-up process.
   (a) Report results and findings.
   (b) Weigh in any effects assumptions might have had.
   (c) Make recommendations for model improvement or future additions.

2.8. Socioeconomic Framework

Demand and supply drivers are estimated econometrically based on historical data, socioeconomic drivers and key assumptions. All future models base their approximations on current and past data along with future projections on GDP, population and prices. The same macroeconomic and demographic assumptions/projections are used in all scenarios unless otherwise expressed.

Population

The rates of population growth for each considered country are based on the 2019 Revision of World Population Prospects by the United Nations [5]. The below graph illustrates population change over the two 5-year periods relevant to this study.

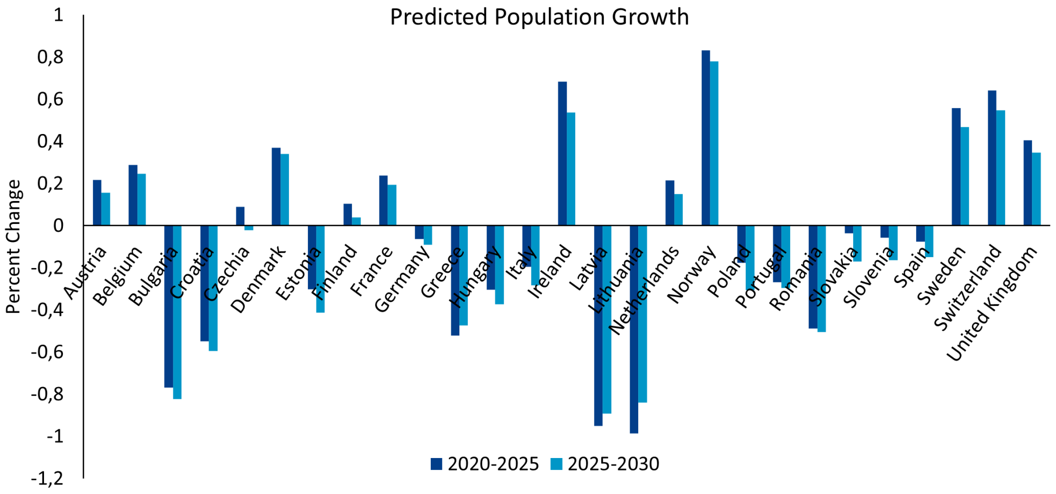


Figure 2.5: Population prediction European countries [5]

Covid-19

The recent COVID-19 pandemic has caused many disruptions in economic trends and brought further uncertainty to the mix. This study considers that the pandemic wont have a large effect on the time period in question. In any case, the economic recovery from the current levels is assumed to stimulate the broadening of biomass feedstock which will result advantageous for local producers. In other words, this study considers that the pandemic will be an opportunity for local supply.

3

Literature Review

This chapter provides an overview of the available literature on biofuel supply chains, their structures and the approaches to modelling them. The aim of this chapter is to highlight the logistical problems encountered in supply chain management/design and how to resolve those issues. Past and recent literature will be used to assess what has already been done, what is currently being investigated and where the future trends/developments are headed. A particular focus will be made on subjects closely related to this thesis topic.

3.1. The Biofuel Supply Chain

Environmental strategies of optimization have been applied in chemical process design for decades. In the past, techniques focused mainly on correcting pre-existing systems and making them more efficient. Schemes for lower energy consumption and cost reduction were applied to specific parts of chemical supply chains. Though successful in achieving the targeted goals, they generally had a narrow scope and boundary. Moreover, the chemical process industry has traditionally responded to the environmental challenges by offering end-of-pipe solutions such as recycling, disposal and waste treatment which don't address the underlying issues, but instead mitigate the harmful effects from them.

In recent times (especially in the last decade), strategies with larger scopes have gained prominence [45]. The main difference between current and past techniques is that now, researchers are more interested in avoiding waste generation rather than minimizing waste in existing systems [46]. The concept is to look at systems holistically by expanding the system boundaries and integrating multiple scales. Zuang et al. [47] reviewed existing chemical production modelling approaches at different scales (metabolism, processes, life cycle, ecosystems) and proposed a multi-scale approach integrating these models into a single cohesive framework. Different scales of modelling are shown in figure 5.19. The proposed framework synthesizes results obtained from models/methods across disciplines and scales to inform process design and decision-making. From the detailed field/lab scale, to the process scale, the supply/life cycle scale and finally the surrounding ecosystem scale, the fusion of these entities creates a larger and more detailed picture of the entire system. Improved performance of the whole system is attained when looked at from this integrated framework. On one hand, the information is more accurate and less assumptions have to be made, and on the other, the connections between low level and high level parameters are more visible. For example, options within the supply chain with negative economic potential or arbitrary combinations can be screened out early in the design (saving computational time). While this method provides unique and new insights into the emergence of potential biofuels, the downside is that it requires more data and computational power than previous methods.

In figure 5.19, the first level of analysis contains field trials and laboratory scale experiments. This can involve research such as fuel property estimations, effects of fertilizer on biomass yields, etc [46]. The research is focused on understanding the working mechanisms or principles, or determining the feasibility of new technologies and techniques. The information obtained at this scale is often of high quality (low uncertainty) and is used to parametrize process models.

The following tier (process scale) uses agricultural crop models as well as traditional process design analysis to simulate biomass yields, water requirements, carbon flux, etc. under different constraints and crop management operations. This tier also addresses the conversion of biomass to fuel and the energy flows involved.

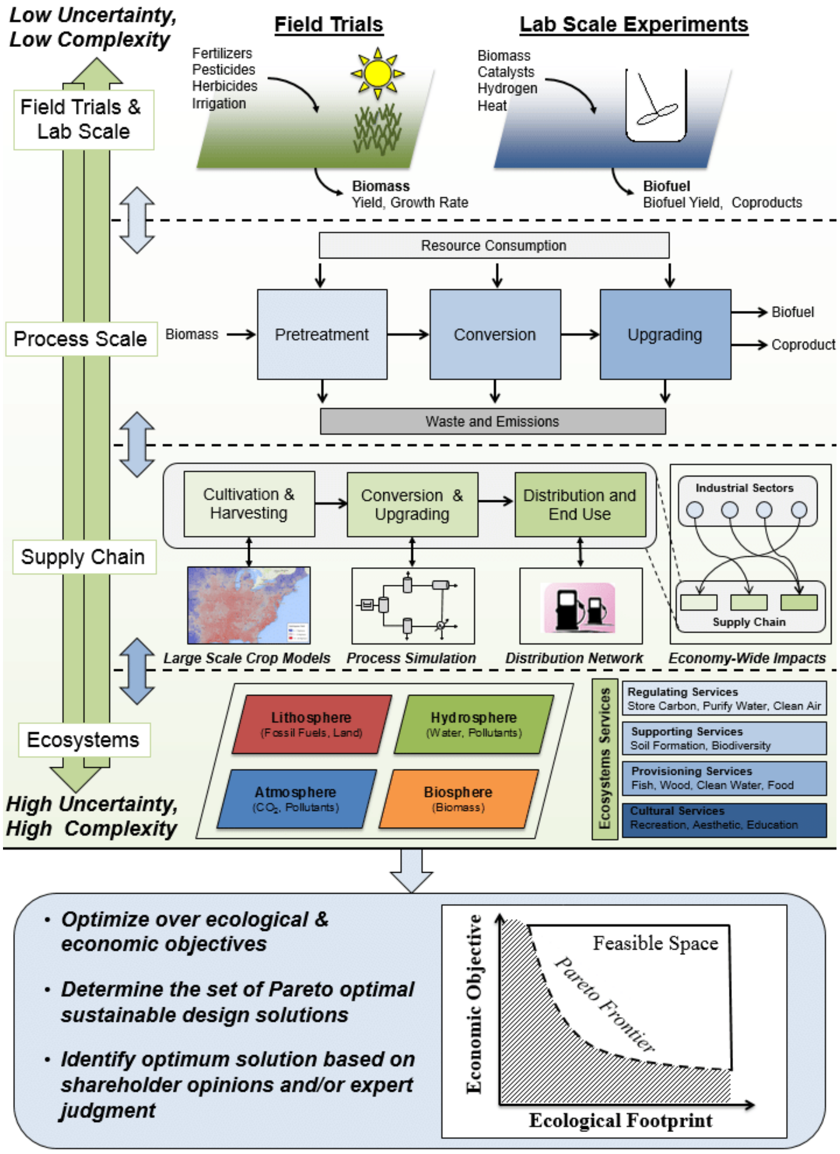


Figure 3.1: Modular Multi-scale, Multi-objective, Biofuel Supply Chain Optimization Framework.

Models at this scale are usually used for the maximization of material and energy efficiencies, while also minimizing costs. Since life cycle considerations are not considered at this level, an analysis solely on this tier could result in unsustainable design choices.

The third level of analysis extends the boundary to include energy, material and emission flows throughout the entire supply chain. This is done by using a an LCA over the entire life cycle. Analysis at the supply chain/life cycle scale is often focused on improving efficiency and mitigating environmental effects over the life cycle of the product. However, the methodology used fails to consider the impacts of biofuel life cycles on ecological surrounding, such as the effects on nature, biodiversity, food, poverty, etc. This is where the final tier comes in, the ecosystem scale. Since the ecology is ultimately what sustains the production of biofuels, it must be considered to some extent in the analysis. Some examples of ecological goods/services are food, timber, water, clean air, maintenance of biodiversity, climate regulation, etc.

The development of biofuel pathways requires addressing the alternatives that exist throughout the life cycle. Decisions based on the consideration of one criterion, such as economic or environmental optimization, can have the unintended consequence of trading it for another. That is why many studies have developed models to capture several criteria. For example, the SCORE model made by Krajn and Domac [48], consists of a collection of excel sheets that estimate 15 socio-economic and environmental aspects of increased use of biomass from the forest in order to make decisions and trade-offs. Another model, OPTIMASS, was developed by De Meyer, Cattrysee and van Orshoven [6]. Unlike the SCORE model, OPTIMASS took the modelling a step further by including an optimization of the location and type of potential biofuel facilities. Additionally, the model considers the re-injection of by-products from the conversion process back into the biomass supply chain. More on this model and how these models are developed can be found in section 3.2.1.

To consider the emission, energy and cost flows, the supply chain should be looked at from the third level of analysis. As explained, an LCA is one of the most popular approaches to capture the emissions throughout the life cycle of a fuel. By quantifying the likely impact of production prior to its implementation, environmental damages can be avoided before they become fixed in the supply chain.

The supply chain at the third level can be described as a system with various stages and interconnected nodes that link the biomass with the final fuel product. From harvesting, pre-processing, transporting, converting, storing and distributing, the process has a number of steps depending on the fuel type. With the differing conditions, a range of costs, emissions, and environmental effects can be achieved. A basic overview of the steps in a biofuel supply chain is presented in figure 3.2. As can be seen, the biofuel supply chain is the six-stage process in which raw feedstock from a source is converted into fuel and delivered to the end-user. The major entities in a BSC are the source sites (and types), storage/collection sites, processing sites, and demand locations. The supply chain is further divided into three segments according to the products and operations observed [6]. The upstream covers from the feedstock production to the delivery to the conversion facility. The midstream captures the conversion process itself, which is usually considered as a black box with the input of biomass and the output of bioenergy/by-products. The downstream segment deals with the storage and distribution of the fuel to the end-users.

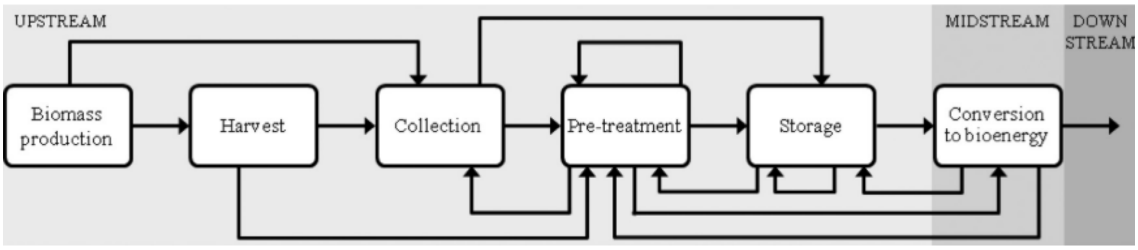


Figure 3.2: The six-step biofuel chain [6].

Due to the complexity of supply chains, most models found in past literature focus on one or two segments of the supply chain at a time. Since most of the obstacles curbing the development of biofuels are encountered within the characteristics of biomass products [6], a large amount of literature and models relate to the optimization of the upstream segment. Usually, these models are limited to a specific biomass supply, collection and conversion. Nonetheless, there exists a wide array of literature covering the other two segments, though not in as much detail. Advances in modelling techniques, however, are allowing for integrated modelling of several steps. A more simplified version of the framework can be seen in figure 3.3. In this example, the feedstock travels directly from collection site to the refineries and then to the customers.

3.1.1. Biomass Cultivation and Harvesting

The first node in the chain pertains to the cultivation and harvesting of the feedstock. As explained in Chapter 2, the feedstocks considered in this project are of second generation. Therefore, instead of the cultivation and harvesting, what is more relevant is the collection and production of the feedstock itself.
It is important to consider several aspects pertaining to the production of these feedstock such as:

- The seasonal nature and annual variability of the biomass supply.
- The location and production capacity of each feedstock at each site.
- Cost and emission related data at each site. (collection, packing, etc.)
- The chemical properties and physical state in which the feedstock is collected.

This step in the supply chain is essentially tied into the biofuel supply. Many statistical reports have outlined the supply of biomass for certain biofuels in geographic areas but this is usually done under broad assumptions

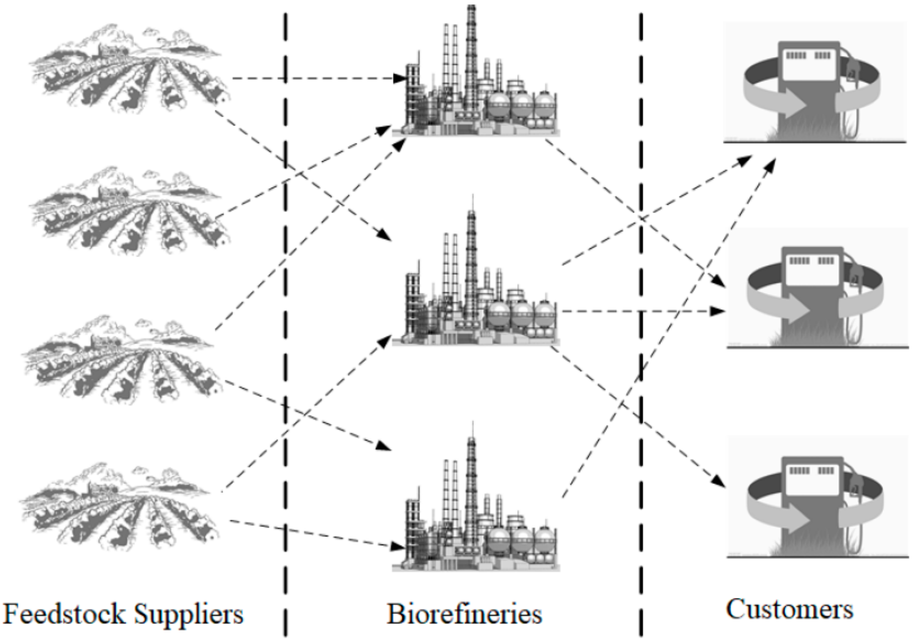


Figure 3.3: General framework of bioenergy supply chains [7]

and with a large margin of error. Due to the complexities involved in modelling biomass supply, it presents a problem in itself, which is why most authors use a data-driven approach. This entails using the data from external sources to model the biomass availability.

3.1.2. Biomass Preprocessing and Biofuel Production

Once the biomass has been collected, it must be transported to the fuel conversion facility. However, for many types of biomass, it is necessary to first go through a pre-processing whereby the material is refined before being taken to the facility. This can be a result of the specific material and process considered, but also for transportation purposes. It can be uneconomical to transport low energy feedstock, especially over long distances. Thermal and chemical processes are used to densify the material, remove water content/contaminants and improve quality/processing performance [49]. In specific, the moisture and ash contents of the product are usually considered in literature. These properties affect the total cost of production and have an impact on the network design of the SC.

On top of that, the biomass supply may be seasonal, but the demand for transportation fuels is year-round. In this case, storing the feedstock might be necessary and the collected biomass must be accumulated for continuous use in biofuel production throughout the year. This can be done either before or after the conversion process and many times, low-cost storage solutions are chosen, such as on-field biomass storage. However, side effects include biomass degradation, heating value reduction, and potential health risks, mainly because of the presence of a high water content.

3.1.3. Biofuel Distribution and End Use

The last two components in the BSC are biofuel distribution and end use, which ensure that the biofuel products can cost-effectively reach their markets and be used by consumers. The distribution is the transportation of the biofuel from the production facility to the final user. This is the final step of the transportation process, and is highlighted because this usually occurs in a bulk process and therefore can require large shipments on a tanker vessel (for transportation cost reduction). The modes of transport between the preceding stages include rail car, barges and trucks. Transportation of fuel through pipelines exists (mainly for oil and petrol), but that isn’t an option for these specific fuels as they can be corrosive to the existing piping [50]. This final step is linked to the biofuel demand, which ultimately determines how much and at which location fuel is needed.

3.2. Modelling Approach

There is a limited amount of literature on second generation biofuels or on biofuel supply chains in the maritime industry. However, the literature on modelling crop-based biofuel supply chains for the aviation, automotive and heating sectors is extensive and well documented. In terms of the processes, they are almost the same, thus these sources along with proper assumptions can achieve a realistic modelling approach.

In BSC modeling and optimization, all factors in the supply chain are modeled as a set of nodes, and all possible interconnections between these nodes are modeled as a set of arcs [49]. This modelling architechture is called a superstructure and embeds all possible alternatives. The nodes typically represent the available biomass suppliers, preprocessing facilities, biorefineries, and final demand users. The arcs typically stand for the transportation of biomass and biofuels between the nodes. At each arc, the superstructure allows for a choice among different transportation modes, eg, truck, rail, barge, or pipeline.

The supply chain model can be broken down into an infinite amount of variables and factors. The higher the number usually implies higher complexity and computational time, but also higher accuracy (if the input is also accurate). Bravo et al. and Wee et al. [51, 52] suggest that in order to keep a hierarchy of decision variables, they be split up into strategic, tactical or operational variables. The strategic decision making level involves all variables which are long term and concern the design of the supply chain. Tactical variables are decisions that are made from monthly to yearly. These usually have to do with the planning and scheduling. Depending on what is to be optimized, the respective decision level can be selected and the model can be designed accordingly to that level of detail. A closer explanation of these decision levels is continued below.

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

Strategic Decisions

Strategic decisions are those decisions that have an influence over years, decades, and even beyond the lifetime of the project. Once a strategic decision is made and is implemented, it is very unlikely to be altered in the short term. The most crucial strategic decision is the design of the BSC network, which includes the selection of biomass suppliers, location of preprocessing facilities and biorefineries, assignment of customer serving areas, and transportation links that connect different sites and deliver the biomass/biofuel across the BSC [53]. The selection of biomass-to-biofuel conversion technologies and corresponding infrastructures is also an important strategic decision. Different technologies vary in yield, energy consumption, feedstock requirement, and capital and operational costs.

Tactical Decisions

The tactical decisions act within the contraints developed in the strategic decisions to ensure good cost and benefit to the system. Such decisions include planning and control, for example ensuring sufficient biomass is available (and from which source) to meet the production plan and whether storing is necessary. In the case that there wasn't enough feedstock available, a tactical decision could be to allocate feedstock from a different source.

Operational decisions

Operational decisions are those decisions that are adjusted more frequently in correspondence to the current external and internal conditions, which usually have impacts for no longer than a year or even a day. These are usually used not for the design but for the optimization of the process once the system is in place.

3.2.1. The Mathematical Model

To represent real-world situations and determine the most optimal outcome, mathematical programming models are used. In general, these models involve an objective function, decision variables and constraints. This implies that the values of the decision variables are calculated in such a way that optimizes the objective function while satisfying the restrictions put forth by the constraints. The mathematical model used can be categorized as deterministic, stochastic, hybrid and IT-driven.

For deterministic models, the parameters are known and are fixed with certainty. These parameters can include capacity limitations, demands from each customer, transportation capacities, etc. On the other hand, in stochastic models, (some) parameters are uncertain and random; they are also called probabilistic models. These uncertain variables can be useful to model factors which are arbitrary/ambiguous such as droughts, machine failure, delays, price fluctuations, natural disasters, etc. A key challenge with biomass supply chain uncertainties is that they are distributed over multiple timescales. For example, variations in supply and demand are short-term uncertainties at the operational level while factors such as government policies are strategic uncertainties affecting a longer time period [50]. However, these models can become complex and difficult to solve. Stochastic programming also suffers from inherent weaknesses which make it difficult for practical, real-life applications [54]. For example, in order to accurately model a random variable, its probability distribution should be know. In practice, this is rarely the case, and determining the actual probability distribution requires a lot of time and money [54]. A way around this and still of accounting for uncertainty is with robust optimization. Robust optimization depends on the type of problem at hand, but in biofuel supply chains, usually entails using different scenarios to account for probable circumstances. The idea of scenario-based robust optimization was first presented by Mulvey et al. [55]. Their model tries to consider various scenarios to arrive at the preferred level of risk or risk aversion. Hybrid models blend elements of both deterministic and stochastic models, handling uncertainty as well as large-sized network problems. Hybrid methods also combine multiple techniques for handling uncertainties at different timescales, which might be a promising approach for balancing computational tractability and solution quality. The IT-driven models integrate and coordinate various phases of supply chain planning on a real-time basis using application software. However, IT models are usually utilized to optimize the supply chain on an operational level [56].

Models are further classified into single-objective and multi-objective. These objectives can be thought of as quantifiable performance measures. Some of the most common ojectives/optimization criteria found in literature are:

- Minimize total cost (TC)
- Maximize total profit (TP),
- Maximize net present value (NPV),
- Maximize financial income (FI),
- Minimize transport distance (TD),
- Minimize transport cost (TRC),
- Minimize greenhouse gas emissions (GHG),
- Maximize energy return in the conversion facility (ER),
- Minimize energy consumption in the supply chain (EC),
- Maximize net energy profit (EP),
- Minimize environmental footprint (EF),
- Maximize the number of jobs created (CJ),
- Minimize social footprint (SF).

The solution method to the proposed problem can be formulated and solved in a number of ways. However, mathematical programming is one of the best developed and most utilized branches of operational research [57]. Within mathematical programming, the problem can be formulated and solved though linear or non-linear formulations, though linear is more common. An extensive review on optimization modeling of biomass supply chains is presented by Yue et al. [50]. Existing optimization models for biomass utilization networks use mixed-integer linear programming (MILP) or mixed-integer nonlinear programming (MINLP) formulations. MINLP can account for non-linear functions, economies of scale, etc. One advantage of mixed-integer linear models when compared to linear programming is that by means of integer variables the investment costs of facilities can be separated from the operation costs. Mixed-integer linear models are capable of making decisions related to location, technology selection, capital and investment, production planning, and inventory management. Among the mathematical programming techniques, MILP is the most commonly applied technique and is used at all decision levels whereas non-linear and integer programming are only used to optimize strategic decisions. [56]. For instance, Leduc developed a Mixed Integer Linear Programming (MILP) model to determine the ideal geographic locations and sizes of wood gasification plants in Austria for the production of methanol [58]. His goal was to reduce total costs, which were comprised of biomass supply, transport, capital and operating costs of the plants. In another example, De Meyer et al. [6] used a generalized MILP model (BIOMASS) to optimize over strategic and tactical decisions to explore the possible effects of different feedstocks, technologies and policy changes on the sustainability of the biofuel SC.

Usually, in literature the measure(s) to be optimized is either some type of costs or emissions, but through a multiple objective formulation can include both and/or others. When using a multi-objective optimization, however, the optimal solution is not at a single point but instead a set of Pareto-optimal solutions. In this set, it becomes impossible to improve any objective without worsening the other. Any point outside this set is either infeasible due to the constraints or sub-optimal. This is often the case for conflicting criteria. For example, a study by You and Wang performed a life cycle optimization of biomass-to-liquid supply chains to minimize total annual costs and also the greenhouse emissions over a 12-month period [59]. However, it was found that the lowering emissions had the direct effect of increasing costs. With a multi-objective formulation, a compromise of both goals was reached. In this way, the unintended consequence of trading one problem for another can be avoided and a balance can be achieved.

Regardless of the chosen method, the optimal solution is always within the superstructure. Therefore, the design of the superstructure, which accurately models reality is the key to achieving a quality optimization. Akgul et al (2011) used a MILP model to determine the most efficient planning of a bio-ethanol supply chain in order to reduce total costs. The model was built to optimize the locations and scales of the bio-ethanol production plants and flows between regions as well as transport units required. In this study the following elements were considered:

- Biomass cultivation and biofuel production rates
- Geographical biomass availability
- Transport (price, modes, distances, and availabilities)
- Capital investment costs
- Locations and scales of biofuel production facilities
- Flows of biomass and biofuel between regions
- Locations of biofuel demand centers and their biofuel demand
- Biofuel production costs and unit biomass cultivation
- Modes of transport for delivery of biomass and biofuel

The proposed mathematical models can be solved to optimality nowadays through the use of commercial linear problem solvers. CPLEX, GAMS, GUROBI and Matlab are among the most popular solvers implemented in these problems. However, the running time of these solvers greatly increases when integer variables are added. Non-linear formulations are even more difficult since the solution only converges to a local optimum (unless convexity properties hold). An important piece of advice, suggested by various authors on this subject is to reduce the superstructure as much as possible before implementing it. This serves to reduce the computational time and to get rid of alternatives which are inviable. This entails, for example, the removal of candidate sites which are not promising, or cutting off unrealistic arcs.

3.2.2. Data Modelling

In every model, there is a set of inputs that provide all of the necessary information to solve the problem. These inputs, such as costs, capacities, supply, demand, etc. can be written directly into the model or stored in an external database and be transferred into the model. When storing data externally, the data is more accessible and can be changed with greater ease. It also allows for different tools to be benchmarked in the same case studies. The reference data model, is meant as the blueprint of the database component of information and decision support systems related to typical biomass based supply chains [60]. The role of a data model is to list, analyze and structure in a logical way the set of data required or produced by a software application. Though almost all models use a (external) database, there isn't a consensus on the structure and the data needed in the optimization model. The different approaches and lack of transparency led De Meyer et al. [6] to create a generic reference data model to achieve a standard exchange format. The decision support system proposed combines three modules: (1) a database module, (2) a query module, (3) a decision module (figure 3.4).

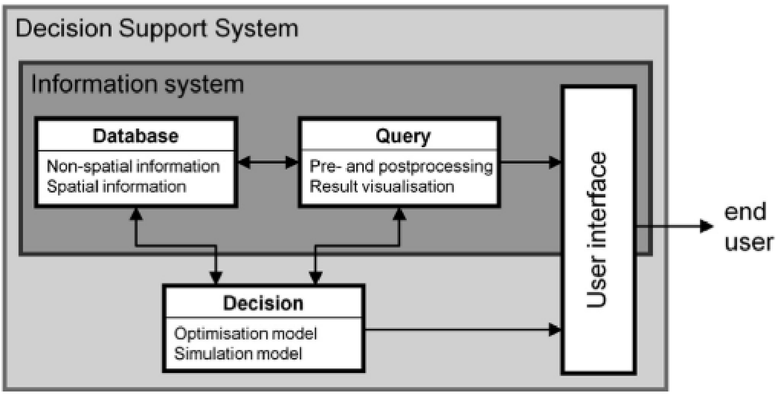


Figure 3.4: General architecture of a spatio-temporal decision support system for biomass-based supply chains [6]

The database module stores the input data of the optimization to characterize the problem. The database is linked to a GIS-based query module that enables the user to visualize and process spatial (i.e. geographical) data and results. The decision module encompasses the tool to optimize/simulate the supply chain.

3.2.3. Modeling Sustainability Issues in the Biofuel Supply Chain

Biofuels are regarded as renewable alternatives to conventional petroleum-based fuels and can lead to a reduced impact on the ecosystem. For these expectations to be met, the objective of the biofuel optimization should be centered around the sustainability aspect. It makes sense that for this to be true, the entire carbon footprint of the biofuel should be accounted for. To do so, an option is to try out all possibilities and compare the results afterwards. However, this method is cumbersome, and what is more efficient and commonly used is to incorporate multiple objectives into the objective function.

If supply chains are to be sustainable in the medium to long term, they have to appeal to a wide range of stakeholders. They must be economically attractive, socially acceptable and improve environmental aspects. In other words, they must offer solutions not problems. In situations where trade-offs between different objectives are necessary, stakeholders need to agree which are most important in a given context and how systems can be designed to minimize undesirable effects while maximizing the objectives. These trade-offs can be achieved through sensitivity analyses whereby the effects of one aspect and others can be visualized.

3.3. Future Trends

Biofuel supply chains are often compared to petroleum supply chains, especially in the downstream component (after the fuel conversion). However, the upstream components are very different. Further, the majority of literature on biofuel supply chains is focused around one fuel in a small area (nationwide). Few literature exists on large-scale supply chains for multiple fuels. Therefore, future modelling should put more emphasis on the upstream component. It is also desirable to build a robust model that can be tweaked for different types/qualities of biomass feedstocks and fuels.

Recent studies in this field have brought novelty to the optimization process either by considering specific supply chain structures or presenting new solution methods. For example, Lopez Diaz proposed a MINLP model for the design of a bio-refining system in Mexico. Particular to his model, Lopez modelled the three segments of the supply chain, including the cultivation of the crops and linking it to water use. This is seldom done in literature, as the majority of published works only consider the products when they are ready to be harvested. In another example, Castillo-Villar developed a two stage linear stochastic programming model to minimize costs related to transportation, location, technology and quality with a case study in the state of Tennessee. The stochastic parameters included ash and moisture contents. This was relatively novel, as few studies focus on variability.

Although a large number of contributions are available in the field of biofuel supply chain modelling, there is still room for further investigation. Particularly for maritime fuels, mathematical models addressing the BSC are scarce. Based on the analyzed literature and the current trends in literature, the following research gaps claim for deeper attention:

- The BSC using multiple feedstocks and end products, considering the medium-to-long term supply particularities of the raw materials.
- More in depth attention and modelling of the upstream component of the processing.
- Robust optimization and a higher level of detail with regards to the input data for data modelling.
- A connection/mathematical relationship between the supply and demand. Most models make use of existing data and assumptions to consider the supply and demand aspects separately, while in reality they depend on each other and are tied together through a sort of feedback loop.

To the best of the authors' knowledge, there is currently no published work on the optimization of biofuel supply chain networks at the EU level by 2025 that considers the production of second-generation feedstocks. Though literature on the upstream component of most biofuel supply chains could be advanced, in particular to the (international) maritime industry, more emphasis should be placed on the downstream component and the port-to-port distribution.

In order to address the aforementioned gaps, this thesis develops a Multi-Objective MILP model to to design and optimize the supply chains of bio-ethanol, bio-methanol and bio-LNG from multiple feedstock sources , projecting strategic supply chain decisions in the medium term. The main contributions of the present study lie within the novel fuels being looked at, the robustness of the framework developed, the focus on the upstream supply-chain segments, the lengthy time-frame in question, and the built-in open choice of fuel production.

4

Model

This chapter bases off of the literature study to propose a formulation of the problem in mathematical terms. The goal of the chapter is to provide a representation and implementation that considers the aspects mentioned in chapter 2.

Though this chapter creates the framework to solve the problem at hand, it uses the data developed in the supply and demand in chapters 5, 6 as well as the techno-economic parameters in chapter 7 as inputs. Those chapters are supplementary to this one and should be considered jointly.

4.1. Modeling Framework

In this paper, a MILP model is formulated to represent the biofuel supply chains and allowing the selection of fuel conversion technologies, biomass supply locations, and the logistics of transportation from resources to conversion and from conversion to final markets. The MILP model is used to design and analyze optimal distribution and conversion systems, using a realistic data set covering the European member states (see chapter 2.7).

The modelling environment is set up as follows: the input of the model, which includes the supply and demand scenarios, are read from excel and connected to a GIS (Geographic Information System) interface which allows for visualization of the data. The inputs, along with the rest of the parameters are loaded from excel sheets (external database) onto python. A GUROBI optimization package is used to solve the optimization problem under the given inputs, decision variables and constraints. The results are exported again to excel and connected to the GIS software to visualize the final results. Additional GIS interfaces are coded directly into the python program to achieve specific visuals that are desired.

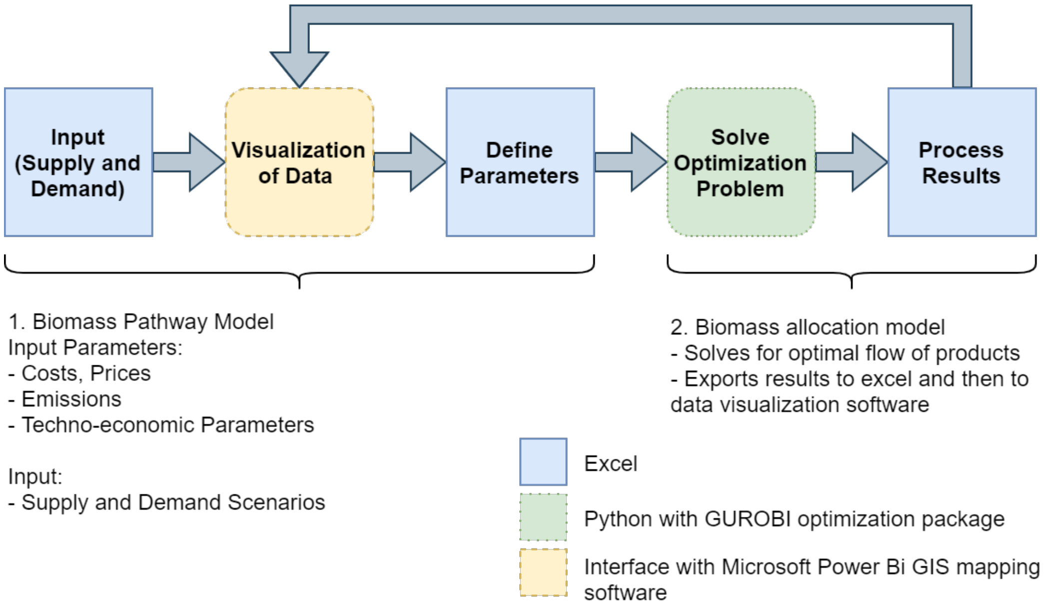


Figure 4.1: Visualization of the modelling framework and environment.

4.2. Main Model Features and Assumptions

The proposed problem can be formulated mathematically as a transhipment problem. In this set up, the network nodes have both input and output simultaneously, with additional supply and demand (origin and destination) points. This scenario is common in supply chains where material arrives at some warehouse/processing facility and is transferred to the final user through another mode of transportation. A formulation of this sort is not as common in BSC literature as other problem formulations (for instance, warehouse location problems/discrete facility location problems). The main consideration taken in making this decision was the relatively short (with respect to infrasructure changes) and vincinal timeframe of the problem. Instead of optimizing for future, long term decisions, the system uses current data to create a realistic assumption of what the future will look like and optimizes those scenarios. In other words, the system doesn't make recommendations on long-term decisions such as determining new biorefinery locations or large infrastructure investments. This is due to the fact that biofuels are largely seen as a transitional fuel (as opposed to a long-term solution) [61], and the temporal proximity of the period in question makes it hard/inviable for any large investments or decisions to be made. Further, any decions made for large scale investments, might become obsolete at the end of the time period due to new incumbent technologies. Therefore, the focus will be on determining optimal flow and demand satisfaction attainability under the different scenarios and current technologies.

The superstructure of the model itself consists of four echelons, each with their respective nodes. The first echelon, the collection point, consists of 27 nodes (one for each country) which have a certain supply of each type of considered biomass for each year in question. The biomass is collected at a certain point in a country and transported in its raw state to a preprocessing facility within the same country. At the pre-treatment plant, all biomass types go through a physical conversion and are densified to remove nearly all moisture content. Once this is done, the pre-treated product is ready for transport. From the country, the biomass travels to a nearby conversion facility where it is converted into one of the three fuels. In this study, it is assumed that biofuel conversion and upgrading are conducted in the same facility. Therefore, the product that leaves the conversion plant requires no further processing. Since the conversion facilities are also the ports (demand sites), once the fuel has been produced, it can either stay at the same port (and contribute to the fuel demand quota at that same port), or be transported by a tanker vessel to another port to meet *its* demand quota. All decisions made in the system are ultimately based on the reduction of total system costs and emissions. Since these decisions mainly include network design choices (transportation routes, quantities, selection of biomass suppliers, and selection of conversion technologies for a type of fuel), all decisions are made at the strategic and tactical levels. Further, the model reflects a "pull" demand model whereby the system only makes as much fuel as is required by the demand.

The model is described by six sets of indices. Set $\boldsymbol{S}$ contains the list of considered countries, set $\boldsymbol{P}$ includes the ports to which the fuel must be distributed to. Again, the port locations also serve as the biorefinery locations, however, these two sets must be different in name to distiguish them. Set ***B*** contains the five types of considered biomass available, set ***I***, the intermediate products (which are the same as the feedstocks, but with different physical properties), and ***F***, the three fuels that can be produced. Lastly, the set ***T*** has the discrete time intervals.

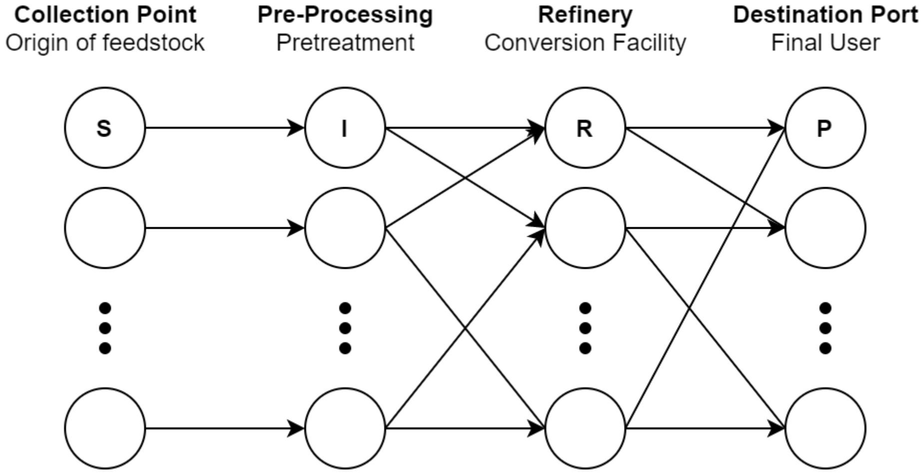


Figure 4.2: Model superstructure

Table 4.1: Chemical and physical properties of the different fuels.

Indices

Set	Definition	Description
S = {..28}	Country	The 27 considered countries of origin for the feedstock
R = {..15}	Refineries	The 15 available integrated refineres across the EU
P = {..15}	Ports	The 15 considered ports for refining and final distribution of the fuels
B = {..5}	Biomass Types	MSW, Sewage, Manure, Wood residues, Agricultural Residues
I = {..5}	Intermediate Products	Pretreated biomass (same as biomass types but with different physical properties)
F = {..3}	Fuels	Bio-ethanol, bio-methanol, bio-LNG
T = {..}	Time Periods	Year in question (2025, 2026, 2027, 2028, 2029, 2030)

Decision variables

Variable	Domain	Definition
$BU_{s,b,t}$	$[0, SB_{sbt}]$	Amount of biomass b ∈ B from country s ∈S used during time period t ∈T
$TI_{s,r,i,t}$	$[0, BU_{s,b,t})$	Transported amount of intermediate product i∈B from country s ∈ S to biorefinery r ∈ R in time period t ∈ T
$SF_{r,p,f,t}$	$[0, TI_{s,r,t})$	Shipped amount of biofuel f ∈ F from refinery r ∈ R to port p ∈ P in time period t ∈ T
$DT_{p,t}$	$[0, DF_{p,t}]$	Fuel energy deficit for port p ∈ P during period t ∈ T
$\Phi_{r,i,f,t}$	$[0, 1]$	Binary decision variable that selects the conversion of biomass b ∈ B into fuel f ∈ F at refinery r ∈ R during period t ∈ T

Objecive Functions

Economic Objective: min TC	Environmental Objective: min TE
= feedstock costs	= emissions from the extraction/collection of raw materials
+ collection costs	+ emissions from processing (pretreatment and conversion)
+ pre-treatment costs	+ emissions from transport and distribution (inland and shipping)
+ conversion costs	
+ transportation costs	

Parameters

Parameter	**Description**
β_b^{bio}	Factor to account for productivity of labor in preprocessing per biomass b [-]
β_s^{labor}	Factor to account for productivity of labor per country s [-]
β_r^{Rlabor}	Factor to account for productivity of labor in refinery r [-]
δ^{drying}	Mass efficiency of drying biomass [%]
$\delta^{milling}$	Mass efficiency of milling biomass [%]
$\delta_{i,f}^{con}$	Conversion yield of converting intermediate i into fuel f [%]
ρ_b^{b}	Density biomass type b [kg/m^3]
ρ_i^{i}	Density intermediate product type i [kg/m^3]
ω^{truck}	Truck volumetric capacity [m^3]
ω^{ship}	Ship weight fuel capacity [DWT]
A_s	Area of country s [km^2]
as	Average speed truck [km/h]
C^{FS}	Total feedstock costs [€]
C^{Coll}	Total collection costs [€]
C^{Pre}	Total pretreatment costs [€]
C^{Conv}	Total conversion costs [€]
C^{Trans}	Total transportation costs [€]
$ce_{s,t}$	Cost of electricity in country s during period t [€$/GJ$]
$ctf_{s,t}$	Cost of diesel in country s during time period t [€$/l$]
cr	Chartering rate for specific ship [€$/h$]
$DF_{f,p,t}$	Total energy demand in port p during period t [GJ]
d_s^{OPre}	Road distance from biomass collection point in country s to pre-treatment in country s [km]
$d_{s,r}^{SR}$	Road distance from country s center to refinery r [km]
$d_{r,p}^{RP}$	Navigational distance from refinery r to port p [nm]
E^{Coll}	Total emissions from the collection of raw materials [gCO_2eq]
E^{Proc}	Total emissions from processing [gCO_2eq]
E^{Trans}	Total emissions from transportation [gCO_2eq]
eff	Emission factor diesel [CO_2eq$/l$]
$efbf$	Emission factor of bunker fuel [CO_2eq$/l$]
fc^{loader}	Fuel consumption front loader [l/h]
fc^{truck}	Fuel consumption truck [l/h]
LVH_b^{dry}	Lower heating value dry biomass b [MJ/kg]
LVH_b^{wet}	Lower heating value wet biomass b [MJ/kg]
LVH_f	Lower heating value fuel f [MJ/kg]
mc_b	Moisture content for biomass b [%]
r	Volumetric rate of loading for front loader [m^3/h]
$rc_{s,t}$	Hourly rental cost of a front loader in country s during period t [€$/GJ$]
$rcap_{r,f}$	Refinery production capacity for fuel f at refinery r [GJ]
$SB_{b,s,t}$	Supply of biomass b in country s during period t [GJ]
sec_b^{drying}	Specific energy consumption of biomass drying [MJ/kg]
$sec_b^{milling}$	Specific energy consumption of biomass milling [MJ/kg]
$ubc_{s,b,t}$	Unit biomass cost for biomass b in country s during period t [€$/GJ$]
$ucc_{r,i,f,t}$	Unit conversion costs of producing fuel f from intermediate i in port p during time period t [€$/GJ$]
$upe_{b,f}$	Unit processing emissions for production of fuel f from biomass b [gCO_2eq/GJ]
$w_{s,t}$	Hourly average wage in country s during period t [€$/h$]
$w_{s,t}^{TD}$	Hourly average truck driver wage in country s during period t [€$/h$]

4.3. Objective Function

Two mathematical functions are proposed in accordance with the sustainability approach:

$$Min\ F1 = Total\ costs \tag{4.1}$$

$$Min\ F2 = Total\ Emissions \tag{4.2}$$

4.3.1. Economic Objective Function

The purpose of equation 4.1 is to reduce the total system costs. Breaking this up into the main cost categories considered, this can be expressed as:

$$C_T = \sum_{t \in T} \left(C_t^{FS} + C_t^{Coll} + C_t^{Pre} + C_t^{Conv} + C_t^{Trans} + C_t^{Deficit} \right) \tag{4.3}$$

The total costs are the sum of all costs across every time period. As expressed, the total system costs in each time period are divided into the five different costs associated at each phase in the supply chain plus the deficit cost. Starting from the purchasing of the feedstock to the conversion and transportation.

$$C_t^{FS} = \sum_{s \in S} \sum_{b \in B} \left(ubc_{s,b,t} \cdot BU_{s,b,t} \right) \quad \forall t \in T \tag{4.4}$$

Total feedstock costs are measured as the sum of the total amount of each type of biomass collected at each country multiplied by the respective unit biomass price (per biomass type) at each country in each time period.

$$C_t^{Coll} = \sum_{s \in S} \sum_{b \in B} \left(\frac{BU_{b,s,t} \cdot (w_{s,t} + rc_{s,t} + ctf_{s,t} \cdot fc^{loader}) \cdot 10^3}{\rho_b^{wet} \cdot LHV_b^{wet} \cdot \beta_s^{labor} \cdot r} \right) \quad \forall t \in T \tag{4.5}$$

The collection costs can be summarized as the product of the total costs per hour (machine rental, wages and fuel cost) multiplied by the total time needed to load all of the biomass (total biomass energy content divided by LHV, density and loading rate in m^3/h). This is all divided by the productivity of labor in each country.

$$C_t^{Pre} = \sum_{s \in S} \sum_{b \in B} BU_{s,b,t} \cdot ce_{s,t} \cdot \left(\frac{sec_b^{drying}}{LHV_b^{wet}} + \frac{\delta^{drying} \cdot sec_b^{milling}}{LHV_b^{dry}} \right) \quad \forall t \in T \tag{4.6}$$

Costs of pretreatment consist of two parts; drying and milling. The costs associated with these treatments are mainly those relating to electricity consumption and prices for each treatment in each country. Since material is lost during both drying and milling, two constants are added to reflect this; δ^{drying} and $\delta^{milling}$. Due to the drying being performed before the milling, the amount of biomass that reaches the mills is reduced by the factor δ^{drying} as can be seen on the right side of equation 4.6. The total efficiency of the pretreatment process is the product of both pretreatment yields, this is reflected in the constraints of the model.

$$C_t^{Conv} = \sum_{i \in I} \sum_{r \in R} \sum_{p \in P} \sum_{f \in F} \left(\frac{ucc_{r,i,f,t} \cdot SF_{r,p,f,t}}{\beta_r^{Rlabour}} \right) \quad \forall t \in T \tag{4.7}$$

Conversion costs are calculated based on the average cost of producing a unit of the product. In other words, the cost (€$/GJ$) associated with producing one GJ of product from the given inputs. Values are pulled from literature and averaged to approximate the operational costs of production. Again, the productivity of labor is factored in to account for an additional or fewer amount of work depending on the country (or refinery) in which the process occurs.

Lastly, the transportation costs are described:

$$\begin{aligned} C_t^{Trans} = & \sum_{s \in S} \sum_{b \in B} \left(\frac{BU_{s,b,t} \cdot d_s^{OPre} \cdot (fc^{truck} \cdot ctf_{s,t} + w_{s,t}^{TD}/as) \cdot 10^3}{LHV_b^{wet} \cdot \rho_b^{wet} \cdot \omega^{truck}} \right) + \sum_{s \in S} \sum_{r \in R} \sum_{i \in I} \left(\frac{TI_{s,r,i,t} \cdot d_{s,r}^{SR} \cdot (fc^{truck} \cdot ctf_{s,t} + w_{s,t}^{TD}/as) \cdot 10^3}{LHV_i^{dry} \cdot \rho_b^{dry} \cdot \omega^{truck}} \right) \\ & + \sum_{r \in R} \sum_{p \in P} \sum_{f \in F} \left(\frac{SF_{r,p,f,t} \cdot cr \cdot d_{r,p}^{RP}}{LHV_f^{fuel} \cdot av \cdot \omega^{ship}} \right) \quad \forall t \in T \end{aligned} \tag{4.8}$$

The transportation costs are divided into the three legs of transportation. In the first and second segment, (the transport of biomass to the pretreatment facility and the transport of the intermediate to the refinery), the respective products are carried by truck, for which the limiting carrying capacity is volume. Therefore, the total energy content of the used biomass is transformed into total volume and with the carrying capacity and trip distance, the total amount of trips/number of trucks needed is calculated. The costs of truck transport include the fuel costs as well as the truck driver wage, which is different in each country. The last leg of transport is calculated slightly differently. The costs are based on the daily chartering rate of tanker vessels. This includes operational costs such as crew, fuel and docking fees. In the case of a tanker vessel, the limiting factor in terms of capacity is the weight, therefore the deadweight tonnage is used in ω^{ship}.

Additionally, another cost term is added to the equation called "Deficit Cost". In order for the model to allocate fuel to the respective ports and meet the demand while also minimizing costs, it should receive a penalty for failing to do so. In optimization, these variables are called slack variables, but it can be thought of as a "dummy" variable which serves to ensure that the model is inclined towards coming as close as possible to the demand even when there is not enough supply. This variable is also present in the constraints, and without it, in cases where the demand is greater than the supply, the model would be unsolvable and be rendered infeasible.

$$C_t^{Deficit} = DT_{p,t} \cdot cp_t \tag{4.9}$$

The deficit cost consists of the decision variable $DT_{p,t}$ which is the total amount of energy deficit at each port and time period. The cost associated with the energy deficit, cp_t, is the cost of replacing that energy with another clean fuel such as biodiesel or LNG. The value of cp_t is not fixed and will need to be altered for each demand case to a level where the model reaches full demand satisfaction. It is also important to note that although $C_t^{Deficit}$ is included in the total cost function for the optimization, it is not considered in the post-processing values of the cost.

4.3.2. Environmental Objective Function

The environmental impact of the supply chain is assessed on the basis of total greenhouse emissions released during the five-year period. This includes all pollutants that can be associated under a CO_2 equivalence indicator. NO_x and SO_x emissions resulting from production and distribution activities will not be accounted for in this calculation, as they are not greenhouse gasses, and therefore cannot be associated under a common indicator. Further, data on specific pollutant output is not directly available, and as explained earlier, all considered fuels have very low sulfur contents, and NO_x emissions are largely dependent on engine characteristics and the operating envelope of the vessel, whcih are outside the scope of this work.

Throughout the emission calculations and for each part, an effort is made to stay within the LCA accounting rules of the RED II, though as will further be explained in chapter 7, this is not always possible and deviations have to be made from the directive's guidelines. For the considered feedstocks, annualized emissions from carbon stock changes caused by land use change are not accounted for in the calculations, as all biomass in question originate as biproducts and thus do not cause ILUC. Further, any emission savings from soil carbon accumulation, CO_2 capture and geological storage and CO_2 capture and replacement as expressed in RED II are not considered. Accounting for these emission factors is difficult and uncertain. Including them could lead to highly optimistic results, thus they have been excluded from the analysis. The effect of this decision on the final result will be a slight overestimation of total emissions (according to the RED II emission calculation rules). Further, emissions from the manufacturing of machinery are not taken into account.

The total emissions in the system:

$$E^T = \sum_{t \in T} \left(E_t^{Coll} + E_t^{Proc} + E_t^{Trans} \right) \quad \forall t \in T \tag{4.10}$$

Compared to the total cost function, there are two main differences in the calculation. First and most apparent, the lack of feedstock emissions, which was already explained. Secondly, the pretreatment and conversion phases are grouped into one stage and are called emissions from processing, E^{Proc}. This is done in order to be able to use the RED II values as a reference when finding/calculating the total emissions related to the pretreatment and conversion of the biomass.

The emissions related to the biomass collection are proportional to the amount of fuel burned (and the emission factor of diesel) during the loading process.

$$E_t^{Coll} = \sum_{s \in S} \sum_{b \in B} \left(\frac{BU_{s,b,t} \cdot fc^{loader} \cdot eff \cdot 10^3}{LHV_b^{wet} \cdot \rho_b^{wet} \cdot r} \right) \quad \forall t \in T \tag{4.11}$$

The processing emissions are specific to the type of input biomass and fuel output

$$E_t^{Proc} = \sum_{r\in R}\sum_{p\in P}\sum_{b\in B}\sum_{f\in F} SF_{r,p,f,t}\cdot upe_{b,f} \quad \forall t\in T \tag{4.12}$$

Lastly, the transport emissions are set up similarly to the transportation costs. The emissions at each leg are related to the distance travelled, number of trips (or number of trucks/ships needed to transport all of the product in consideration) and the emission factor of the fuel being used.

$$\begin{aligned} E_t^{Trans} = &\sum_{s\in S}\sum_{b\in B}\left(\frac{BU_{s,b,t}\cdot d_s^{OPre}\cdot fc^{truck}\cdot eff\cdot 10^3}{LHV_b^{wet}\cdot \rho_b^{wet}\cdot \omega^{truck}}\right) + \sum_{s\in S}\sum_{r\in R}\sum_{i\in I}\left(\frac{TI_{s,r,i,t}\cdot d_{s,r}^{SR}\cdot fc^{truck}\cdot eff\cdot 10^3}{LHV_i^{dry}\cdot \rho_b^{dry}\cdot \omega^{truck}}\right) \\ &+ \sum_{r\in R}\sum_{f\in F}\sum_{p\in P}\left(\frac{SF_{r,p,f,t}\cdot d_{r,p}^{RP}\cdot eff^{ship}}{LHV_f^{fuel}}\right) \quad \forall t\in T \end{aligned} \tag{4.13}$$

4.4. Constraints

With the objectives defined and mathematically expressed, the solution should be constrained to reflect the constraints and limitations of reality. A series of equations will be developed to make sure this is the case.

4.4.1. Non-negativity constraints

The first constraints are the non-negativity constraints. These ensure that all decision variables take on positive values, otherwise the system would minimize the objective functions by allowing the largest negative decision variables, which would yield infinitely low emissions and costs. The lower bound on all decision variables is zero.

$$BU_{b,s,t} \geq 0 \quad \forall b\in B, s\in S, t\in T \tag{4.14}$$

$$TI_{i,s,r,t} \geq 0 \quad \forall i\in I, s\in S, r\in R, t\in T \tag{4.15}$$

$$SF_{r,p,f,t} \geq 0 \quad \forall r\in R, f\in F, p\in P, t\in T \tag{4.16}$$

$$DT_{p,t} \geq 0 \quad \forall p\in P, t\in T \tag{4.17}$$

$$\Phi_{r,i,f,t} \geq 0 \quad \forall r\in R, i\in I, f\in F, t\in T \tag{4.18}$$

4.4.2. Capacity Constraints

Each biorefinery will have a certain capacity of fuel production for each type of fuel. For this to be reflected in the model, a capacity constraints should be made for each refinery. The same goes for the ports. However, it is assumed that ports have unlimited storage capacity when it comes to these three fuels. In reality, a real representation of port LNG capacity can be obtained. Port-specific capacity data for methanol and ethanol however, is not available due to the novelty and lack of current use. Regardless, port capacities for the considered fuels are assumed to be unlimited. This way the fuels will flow to the most economic/least environmentally harmful ports without the constraints of present-day infrastructure, which will be useful for the determination of future infrastructure investments. The following constraint ensures that the maximum fuel production level for each fuel and refinery during every time period is maintained at all times.

$$\sum_{p\in P} SF_{r,p,f,t} \leq rcap_{r,f,t} \quad \forall p\in P, f\in F, t\in T \tag{4.19}$$

4.4.3. Energy Balance Constraints

To ensure that the same amount of product (in terms of energy and including losses and efficiences) flows through the nodes, energy balancing constraints should be placed at each node. To start, the amount of biomass collected should be equal to the amount of intermediate product trucked for each type of biomass and from each country.

$$\sum_{b\in B}\left(BU_{s,b,t}\cdot \delta^{drying}\cdot \delta^{milling}\right) - \sum_{r\in R}\sum_{i\in I} TI_{s,r,i,t} = 0 \quad \forall t\in T, s\in S \tag{4.20}$$

The amount of intermediate product being transported to the refineries should also be equal to the amount of fuel leaving the refineries, accounting for the conversion yield, and efficiencies.

$$\sum_{i \in I} \sum_{s \in S} \left(TI_{s,r,i,t} \cdot \delta^{con}_{i,f} \cdot \phi_{r,i,f,t} \right) - \sum_{p \in P} SF_{r,p,f,t} = 0 \quad \forall f \in F, t \in T, r \in R \tag{4.21}$$

Since some feedstocks have multiple conversion pathways and can be converted into different fuels, a constraint is needed to allow for the selection, but also to prevent double (or triple counting).

$$\sum_{f \in F} \Phi_{r,i,f,t} = 1 \tag{4.22}$$

That is, each inflow of a certain type of biomass from any country at any refinery can only be turned into one type of fuel (otherwise the model would turn it in two all three, which would go against the laws of physics).

4.4.4. Supply & Demand Constraints

The demand constraint ensures that the total demand for each biofuel type at each port is met by the conversion facilities and the transport network. However, the production of a surplus in line with fuel availability is allowed. The purpose of this constraint is to ensure that at least each port is met with the suffice amount of fuel. The slack varible $DT_{p,t}$ is present again here to allow for a deficit when needed.

$$DF_{p,t} - DT_{p,t} \leq \sum_{r \in R} \sum_{f \in F} SF_{r,p,f,t} \quad \forall p \in P, t \in T \tag{4.23}$$

For the supply, the total amount of used biomass of type b in country s during time period t should not exceed the available supply. The following equation ensures this.

$$SB_{s,b,t} \geq BU_{s,b,t} \quad \forall s \in S, b \in B, t \in T \tag{4.24}$$

4.4.5. Other Constraints

Apart from the listed constraints, there is one that deserves attention. There should be some form of constraint preventing the use of infeasible routes between countries or ports. In other words, any route between two points that cannot be achieved realistically, should not be taken. Since these routes are infeasible, they have no value, however, for the model to run, they need an integer value. To make sure these routes are not taken, they are assigned a large number and thus heavily oppose the objective functions making them undesirable for the system.

The rest of the possible and relevant constraints are formulated into the problem, thus there is no need to express them additionally. For example, transportation capacity is formulated into the costs and emissions through the factor ω^{truck} and ω^{ship}, thus no additional constraint is needed to account for this limiting factor. The same goes for any other physical constraint not outlined in this section.

5

Biofuel Supply

In this chapter, the supply of biofuels will be delved into. Starting with an overview of the fuels and their production processes in 5.1, the feedstocks and refinery options will be explored. The estimation of future feasible potential of fuels requires in the first place the estimation of current technical biomass potential. Thus, the chapter looks into current and past trends of feedstock availability to form future predictions.

The planning of biomass use requires the estimation of the available biomass in a locality. The way this stage is addressed varies largely, depending on the sources of information employed. Data might not be available, and if it is, it may not be accurate due to the wide range of sources of information, materials, and socioeconomic areas frequently involved. It is clear that the accuracy of the results will strongly depend on the initial data. In order to be consistent, biomass data will be taken from the same sources when available. The aim of this chapter is to provide insights into biomass resource assessment for energy supply. It is also important to highlight that due to the methodology described in Figure 2.3, the final biomass availability estimated in this study are based on very conservative assumptions.

5.1. Biofuel Pathways & Technologies

Before looking into the existing conversion facilities and feedstock availability, it is important to have an understanding of the potential feedstocks and upgrading technologies/pathways for each considered fuel.

5.1.1. Bio-Ethanol

Bio-ethanol is an ethyl alcohol which currently is the most common commercially produced biofuel (mainly in the road transportation sector), however, shows little compatibility with current marine engines, and cannot be used as a drop-in fuel [27]. First generation ethanol has proven its importance as an alternative to petrol in the automotive industry. Though commonly made by fermenting crops such as corn and sugarcane, it can also be made from second generation feedstock sources. The process for the large-scale production of bio-ethanol is called hydrolysis and the steps include milling, fermentation, distillation, and dehydration.

Since the fermentation process requires sugars, feedstock with high starch and cellulose contents (which are both made of simpler glucose sugars) work best. However, lignocellulosic feedstock such as woody biomass, agricultural residues and grasses are also very common. Because the carbohydrates are not easily accessible for second generation feedstocks, the starting material needs to first undergo a pre-treatment process (biological, physical, chemical or physio-chemical) depending on the feedstock [62]. This step usually alters the chemical composition and surface area, improving the reaction efficiency of the following step. For physical preprocessing, mechanical milling is the most prevalent. This focuses on the reduction of lignocellulosic biomass size by cutting or grinding it into smaller pieces. After this stage the biomass is crushed into a pulp and a microbe such as yeast is added to the mix to break down the sugars. After which the product is distilled to separate the alcohol from the rest of the solids and water. The final purity of the liquid reaches an alcohol content of about 94-96% [63]. Finally, the product is dehydrated in a chemical process to remove the remaining water from the mixture.

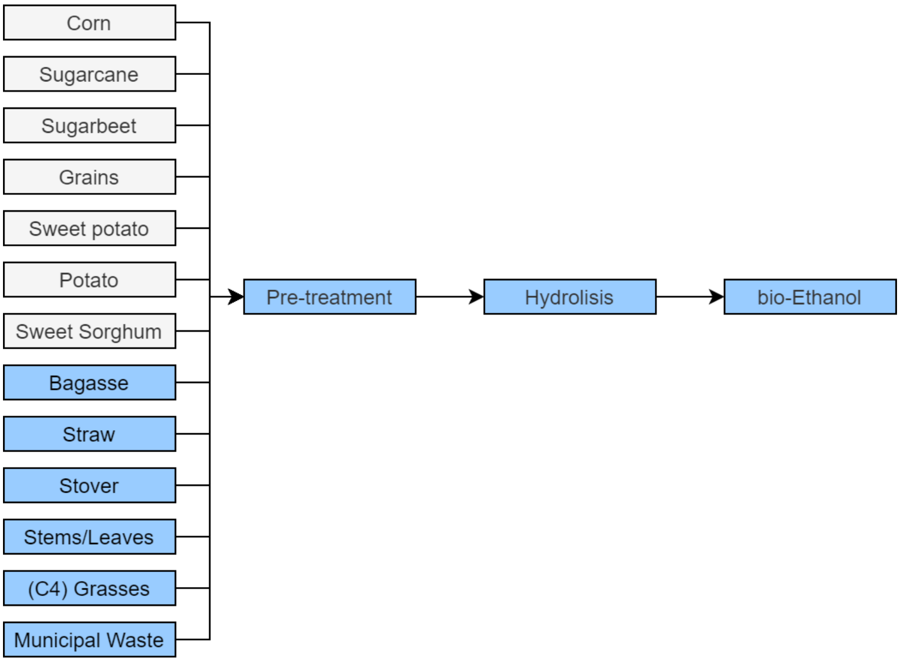


Figure 5.1: Feedstock and production process of bioethanol (first generation feedstocks are color coded in grey).

5.1.2. Bio-Methanol

Biomethanol, another alcohol fuel, serves as a drop-in fuel for diesel engines at a blend rate of 3%. The liquid is usually produced through two main processes; gasification or pyrolysis. However, it can also be produced through anaerobic digestion whereby the released methane is upgraded into methanol. Another type of production method available is called electrolysis which involves the use of electricity, though that is outside the scope of this paper (as it does not originate from biomass). In theory, any carbon source can be turned into syngas (the fore-product of methanol), but current projects focus on using byproducts of industrial processes [21]. The production process of methanol is currently cost intensive, thus at the moment, only waste biomass including industrial residues and biowaste are used for production [28] through gasification.

The feedstocks used in the production include biomass, sewage, biogas from landfills, solid waste, glycerol and black liquor as a byproduct of pulp and paper production. The generation of methanol includes six processes: gasification, gas cleaning, reforming of hydrocarbons hydrogen addition or CO_2 removal, and purification. Biomethanol is considerably easier to recover than the bio-ethanol from biomass. The pre-treatment of bio-methanol includes physical and chemical processes as well as biological. With biological pre-treatments, a fungus is usually added to degrade the lignin and cellulose. Biological pre-treatments are cheap but require longer times, making them unattractive on an industrial scale.

One advantage of methanol is its liquid phase, which is stable at atmospheric pressure and ambient temperature. It can be stored for long term, without losses, and used as a pure fuel [64].

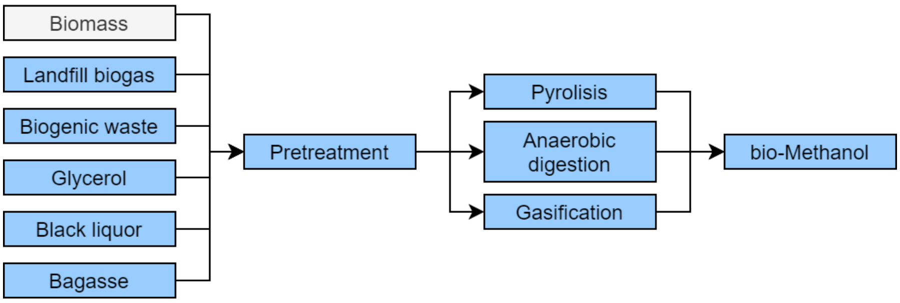


Figure 5.2: Feedstock and production process of biomethanol (first generation feedstock are color coded in grey).

5.1.3. Bio-LNG

Bio-LNG is created from biogas (mainly composed of methane) in a process similar to bio-methanol. Organic waste is mixed with a bacterial digestor in a process called anaerobic digestion whereby the material is broken down and methane is released. The potential feedstock includes cellulose, manure, municipal waste and organic material. In the production process, the feedstock is pre-treated to allow for easier digestion. The bacteria is then added and the digestion occurs. Lastly, the released product is upgraded to remove impurities and then liquefied to increase volumetric energy density.

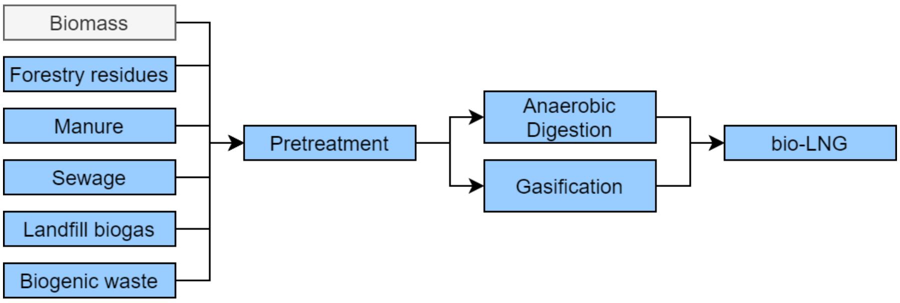


Figure 5.3: Feedstock and production process of bio-LNG (first generation feedstocks are color coded in grey).

One of the advantages of using bio-LNG as opposed to fossil LNG is that bio-LNG is often of better quality, since the bacteria do not produce ethane, propane and butane, which traditionally have to be filtered. As the fuel is chemically identical as fossil LNG, it can be used directly in pre-existing engines, or be used as a drop-in fuel.

5.1.4. Pathway Overview

An overview of the presented feedstock and products along with the incumbent technologie(s) is presented in table 6.3 as an overview. The considered technologies are at a demo/Techno-economic viability (TRL 6-8) or commercial level (9) meaning they are ready or already utilized for the production of these fuels.

Conversion Route	Technologies	Feedstock	Product
Anaerobic digestion	Manure digestion, Co-digestion, All-feedstock digestion, Dry digestion	Slurry (cow and pig), solid manure, sludge, organic waste, maize, straw, grass, agricultural residues	Methane, Methanol
Pyrolysis	Slow/Intermediate/Fast Pyrolysis	Lignocellulosic biomass	Methanol
Hydrolisis	Thermal Hydrolysis	Cellulosic biomass (bagasse, straw, stover, grass, forestry residues)	Ethanol
Gasification	Wood Gasification, Supercritical water Gasification	Woodchips (from forestry production, and primary residue streams), bark, waste wood	Methanol
		All types of biomass feedstocks	Methane

5.2. Feedstocks

The feedstocks considered in this study fall within the boundaries of the feedstocks described in list A of Annex IX from RED 2. A strong focus will be placed on the use of large volume residual flows from agriculture, livestock, forestry and waste. These feedstocks along with the specific examples considered are presented in table 6.3.

The different types of feedstocks can be classified into two categories depending on their most probable energy applications. Lignocellulosic biomass, which is made up from forestry and agricultural residues and fermentable biomass. Since lignocellulose biomass tends to have a moisture content below 60%, these are usually treated through thermochemical processes. Fermentable biomass, on the other hand, usually have moisture contents over 60% and their energy content can be extracted through anaerobic digestion.

For the future supply prediction of the different biomasses, three different scenarios will be developed; a baseline scenario, a low avalability scenario, and a high availability scenario. The baseline scenario will be presented in detail first in the upcoming sections, and then the three scenarios will be compared and explained at the end of the chapter. The baseline scenario is formulated on the basis of current and past data and attempts to create a realistic illustration of the current and future biomass availability in a business-as-usual case. All results are presented in GJ to make them comparable, though this does not imply that these can only be used for energy purposes (for the total availabilities).

Sector	Type of stream	Specific Feedstocks
Agriculture	Production	Almonds, barley, buckwheat, cereals, chestnuts, flax fibre, mixed grains, groundnuts, hazelnuts, maize, (green) maize, oats, pistachio, quinces, quinoa, rapeseed, rice, rye, sesame seed, sorghum, sugar cane, sunfloweer seeds, walnuts, wheat
	Primary residues	Leaves, straw, lignocellulosic material
	Secondary residues	Shells, bagasse, husks
Forestry	Production	Roundwood
	Primary residues	Branches, leaves, bark, roots, stumps
	Secondary residues	Sawdust, black liquor
Livestock	Production	Cattle, goats, sheep, pigs, chicken
	Secondary residues	Solid and liquid (slurry) manure
Biowaste	Production	Paper cardboard, waste wood, animal & mixed food wastes, vegetal waste. Municipal Solid Waste (MSW), common sludge
Sewage	Production	Paper cardboard, waste wood, animal & mixed food wastes, vegetal waste. Municipal Solid Waste (MSW), common sludge

5.2.1. Agricultural Residues

Agricultural residues include a variety of biomass types which can be divided into two main categories: primary residues, which are the materials that remain on the field after harvesting such as straw from wheat, barley, rice, corn, etc. Secondary agricultural residues are the products obtained by processing the primary product. Generally, secondary residues are easier to collect since they're obtained at the processing facility while secondary products have to be collected from the fields [4]. Due to the low energy to weight ratio of agricultural residues, these are usually densified by pelleting, briquetting (or any other industrial process) as a pre-treatment prior to being transported to the conversion facility.

With respect to the primary residues, some of the most important types of biomass include the straw left-over from wheat, cereals and other grains. The factor most significant in determining straw potential is the amount of straw produced per tonne of crop. Competitive, alternative use for litter and animal feeding however, reduces this potential for bioenergy. For example, a study performed in France determined that only an estimated 33% of available straw could be removed without risking soil organic carbon content, and due to other end uses only 23% of the produced straw was actually available for biorefining [65]. These sustainability figures were consistent with other sources. In order to asses the total technical potential, data on agricultural production across European countries is taken from FAOSTAT and Eurostat. The product-to-residue and availability of residues is also available from the Eurostat website and other literature sources.

The residues potentially available for bioenergy production are calculated as the difference between the total produced residues and the sum of residues left on the field and those used for other purposes:

$$AR_{be} = AR_{\text{tot}} - \left(AR_{fl} + \sum \bar{A}R_{u}\right) \tag{5.1}$$

Where:

$$
\begin{aligned}
AR_{be} &= \text{ crop residues available for bioenergy } (tonne/year)\\
AR_{\text{tot}} &= \text{ total amount of residues produced per year } (tonne/year)\\
AR_{fl} &= \text{ residues left in the field } (tonne/year)\\
AR_{u} &= \text{ residues used for other purposes } (tonne/year)
\end{aligned}
$$

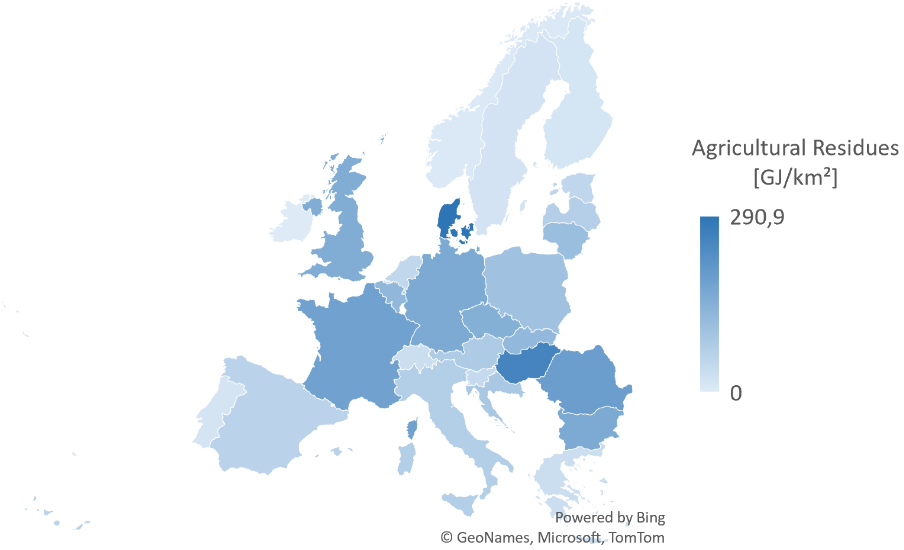


Figure 5.4: Total theoretical agricultural lignocellulosic residues across Europe in 2019 [tonnes].

A 2018 report from the European Commission, reported that in 2015 agricultural land was estimated to cover 42% of all EU land area. Of this, arable land accounted for the largest share – 56%, followed by livestock grazing (25%), mixed crops (13.5%) and various permanent crops (5.5%). Within 2015-2030, EU agricultural land is projected to shrink by 1.1%, primarily driven by the decline in the two principal groups – arable land and livestock grazing – by 4.0% and 2.6% respectively. Mixed crops are expected to expand by 11% [42].

Drastic changes in agricultural land at national level are not forecast by 2030. The seven largest EU countries – France, Spain, Germany, Poland, Italy, Romania and the United Kingdom – account for about 70% of all Utilised Agricultural Area (UAA) both in 2015 and 2030. In relative terms, Denmark, Hungary and Ireland top the EU list with more than 60% of their surface being utilized by agricultural land both in 2015 and 2030 [42]. Although, the amount of agricultural land isn't forecast to increase in this time period, farming techniques have progressively become more efficient, resulting in higher outputs per hectare farmed.

5.2.2. Wood/Forest Residues

Wood and forest residues are produced by the wide-ranging activities performed in the woods. Forests cover around 45% of European land and continue to expand [66]. Since the supply of woody biomass for energy purposes is tied to the supply and transformation of wood for material use, the analysis considers woody biomass used for all purposes, including wood products. The main byproducts looked into are residues of wood processing (recoverable wood product), and wood chips/particles. By the FAO's definition, wood chips/particles are manufactured from a number of sources and originate from coniferous/non-coniferous plants and source (wood in the rough, residues or recovered wood product). Residues of wood processing consists of wood which has passed though some type of processing but also constitures the raw material of a further process [67]. As a rough approximation, the primary wood conversion industry generates about 30-35% of residues per cubic meter of processed wood. Similarly to agricultural residues, retaining a certain degree (15-30%) of wooden debris is usually recommended to reduce the impact of harvesting. This debris serves to improve soil quality and limit negative effects on the ecology. In particular, tree stumps, though considered in Annex IX of RED 2, should not be harvested as their removal increases the risk of soil erosion and biodiversity loss. The theoretical wood residue distribution is presented in the figure below. The calculation for this was done according to:

$$FR_{be} = FR_{wp} + FR_{rwp} \tag{5.2}$$

Where:

FR_{be} = Forest residues available for bioenergy (tonnes/year)
FR_{wp} = wood chips/particles (tonnes/year)
FR_{rwp} = recoverable wood products from processing (tonnes/year)

In this calculation, only primary wood used for applications outside of biomass is considered. In this way, only woody bi-products are considered. Secondary woody biomass comprises all the woody biomass resulting from a previous processing in at least one industry. It includes solid by-products, like chips and particles, other by-products, like black liquor, bark and post-consumer wood.

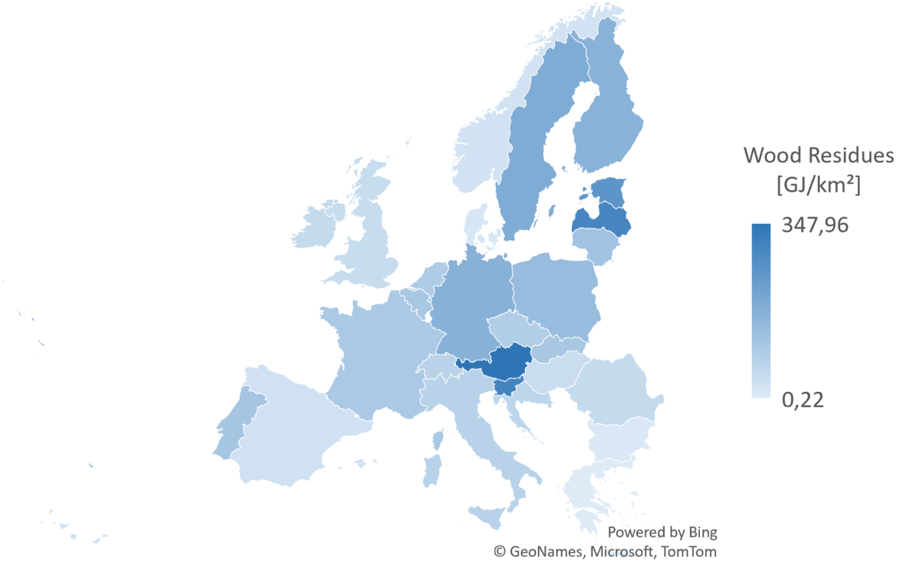


Figure 5.5: Theoretical wood residue distribution across Europe in 2019 [m^3]

The future availability of forest biomass is directly tied to forestry growth in Europe. Growth is projected to remain at the same historic yearly percentages into the ensuing years.

5.2.3. Animal Wastes

Animal manure consists of animal urine and faeces, waste feed and collected bedding which constitutes a large slurry. The use of manure as a feedstock is advantageous in an environmental sense since through its use, the nitrogen utilization of the degassed manure is increased, which reduces the emission of greenhouse gasses.

One of the problems with manure however, is that it has a high moisture content which makes its transportation expensive. Contrary to agricultural and wood residues, it is more difficult to dry manure at the collection site, thus this is usually done at the treatment facility. The manure considered in this thesis is of cattle, pig, sheep, goat and chicken origins.

The collection of the waste differs for each species, and in general only a small quantity of the total production can be retrieved. This is especially true of the grazing animals. In circumstances where intensive livestock rearing systems are employed, the quantity is much larger. The method estimating the theoretical manure potential is based on the total amount of livestock heads and the daily manure production per type of animal. To get the technical potential, only the manure that can actually be collected (produced in stables) is considered. This is found by multiplying by the number of days the animals are in the stables along with an availabilily factor representing the amount collectable from each type of animal per year. Further, after the collection, the manure is used for other purposes aside from bioenergy.

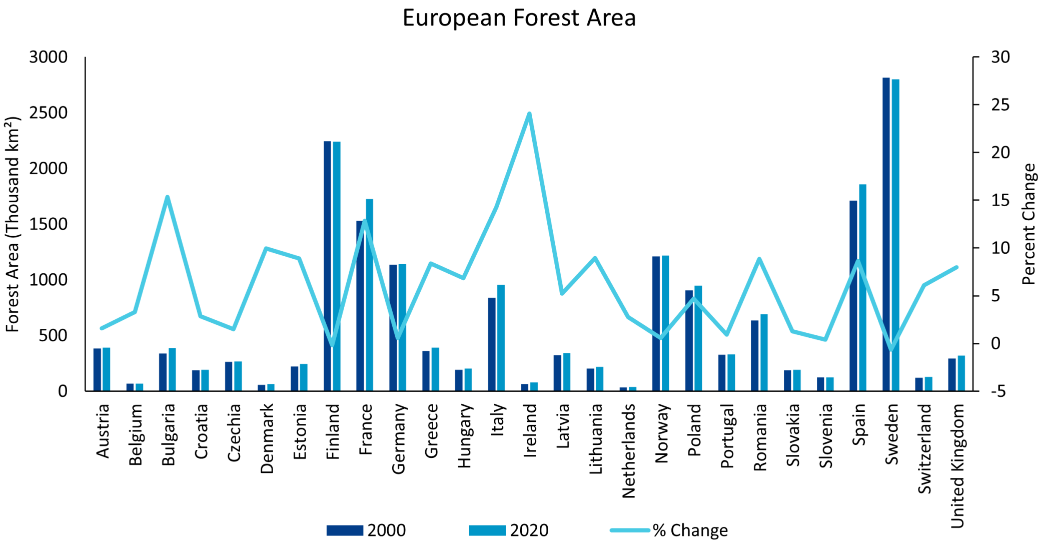


Figure 5.6: Change in forest area and rate of change (2000-2020).

The future availability of manure is correlated to the total amount of livestock, which is influenced by human population and diet. EU meat consumption is set to decline from 68.7 kg to 67.6 kg weight per capita by 2030 [68]. Changing consumer preferences along with the reduction of beef consumption and concerns over the environment and climate change will mean lower numbers of livestock. However, combined with a growing population, total livestock levels are expected to slightly increase by 2030 compared to 2020 levels. On an individual basis, however, the total EU cow herd is set to decline by 7% between 2020 and 2030, pigs will decline by 4.6% [69]. Goat and sheep populations will remain stable, while poultry is the only meat category to grow in this time period (4.6% increase).

$$AW_{be} = \sum N_i * MpH_i * (1 - Mc_i) * AF_i * UF_i * 365 \tag{5.3}$$

Where:

AW_{be} = manure available for bioenergy (tonnes/year)
i = type of livestock (pig, sheep, cattle, goat, chicken)
N_i = number of heads for livestock type i
MpH_i = amount of manure for the livestock type i (tonnes/head)
Mc_i = moisture content for animal i manure
AF_i = availability factor (fraction of manure that can realistically be collected)
UF_i = use factor (fraction of manure that has no other alternative use)

5.2.4. Organic Waste

The Waste Framework Directive defines bio-waste as being comprised of biodegradable garden and park waste, food and kitchen waste from households, offices, restaurants, wholesale, canteens, caterers and retail premises and comparable waste from food-processing plants [70]. However, municipal waste also includes paper/cardboard products, plastics, glass, metals, food and garden wastes and textiles. The collection, management and disposal of this waste is not controlled very well and is still an issue in most countries. In 2017, biowaste accounted for more than 34% of the municipal solid waste generated in the EU-28 and bio-waste from landfill sites contributed to around 3% of total EU greenhouse emissions [70].

Each year the amount of organic waste produced increases. Depending on the treatment operation, the waste management can be classified into five categories; landfill/disposal, incineration/disposal, incineration/energy recovery, material recycling, and composting and digestion [71]. Of these options, only two address the problem of waste management in a sustainable way. As explained earlier, anaerobic digestion of waste generates

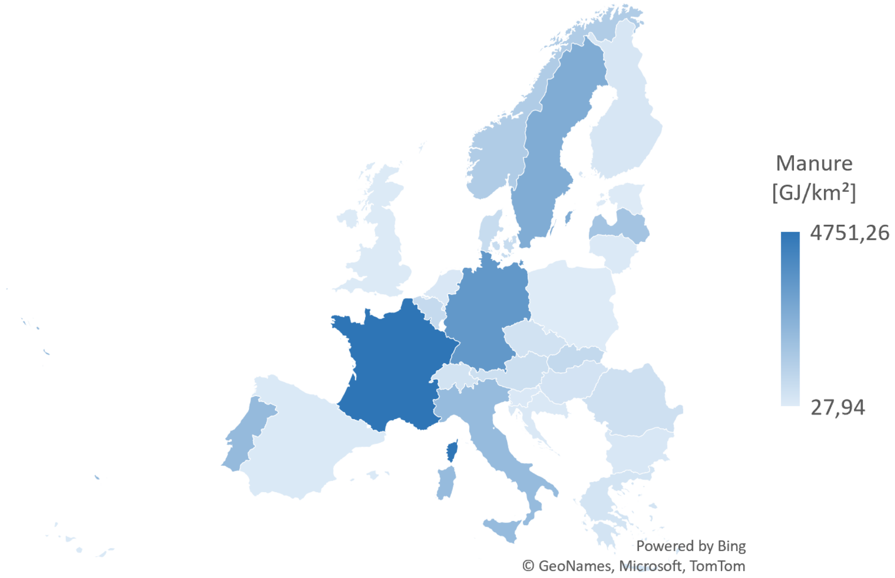


Figure 5.7: Total theoretical dry manure available [kilo tonnes]

biogas which can effectively be turned into bio-methanol or bio-LNG.

Figure 5.8 shows the distribution of municipal waste generation by country in the EU. The amount of municipal waste generated consists of those collected by or on behalf of municipal authorities and disposed of through the waste management system. Figure 5.9 further shows the quantity of organic waste that is currently incinerated for disposal (non-energy purposes), dumped in a landfill or composted/digested. Since, ultimately this fraction of the waste is disposed of or already used for production of biogas/compost, this is considered the potential waste feedstock for production of biofuels.

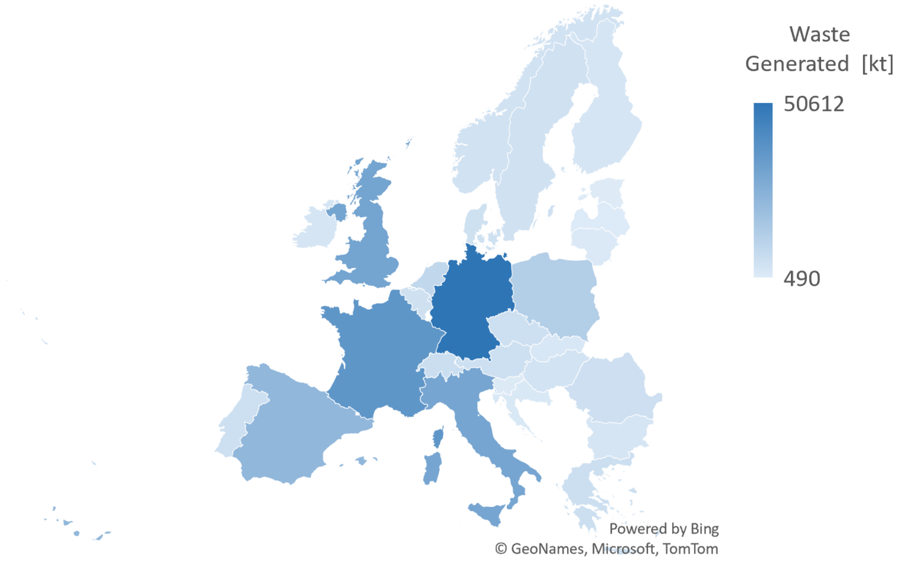


Figure 5.8: Total Municipal Waste Generation in 2020 (kilotonnes).

As can be seen from the graphs, the level of separate bio-waste collection differs considerably across Europe. Many countries are far from capturing bio-waste's full potential, opting instead to incinerate or dump waste in landfill sites. The majority of waste is produced by the larger, central-European countries such as France, Germany, UK, Spain and France, which is logical considering populations. In proportion, though, southern and eastern economies have the highest ratios of untreated waste. These countries show the highest potential for becoming sources of feedstock for MSW as they do not have the infrastructure to direct these wastes elsewhere. However, implementing a separate bio-waste collection system is always complex and can be a lengthy process.

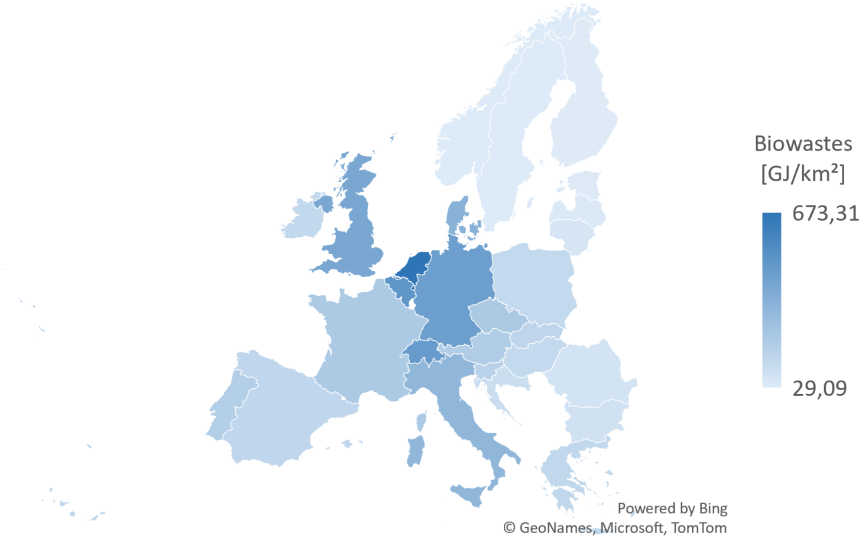


Figure 5.9: Total incinerated, composted/digested and landfill waste in 2019 (kilotonnes).

The future quantities of waste generation depend on the changes in in MSW generation per capita and the population growth of each country. Historically, the amount of waste generation has been increasing since 1980, however a few European countries have managed to reduce the quantity of generated waste [72].

5.2.5. Sewage Sludge

Municipal sewage sludge is a muddy slurry of solids and liquids that results after common sewage (human and other wastes from households and industries) is treated at a wastewater treatment plant. The sludge contains a variety of organic and inorganic compounds in the waste water. Common uses of waste water after treatment include irrigation, pisciculture, forestry, and horticulture [73]. However, large quantities of sludge go unused and are disposed of through incineration, landfill or dumping at sea (dumping of sewage sludge at sea has been prohibited in the EU since 1998 [74]).

Urban waste water treatment in all parts of Europe has improved over the last 30-40 years. As of 2020, the EU-27 countries collected and treated 69% of sewage to tertiary level (most stringent) and 13% to secondary level [71]. These two figures account for 82% of total EU population. Countries where less than 80 % of the population were connected to public urban waste water treatment systems inlclude Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Ireland, Italy, Lithuania, Poland, Romania, Serbia, Slovakia and Slovenia. However, around 96% of total wastewater produced in large (populations over 150,000) European cities is treated due to the development of treatment facilities across Europe in the last several decades [2]. The amount of wastewater produced is set to increase with population (the production of wastewater per capita for each country has remained mostly stable over the past ten years) and further treatment plants in development. With these trends in mind, it is safe to assume that by 2025 up to 90% of EU sewage will have access to a wastewater treatment plant and will be available for other purposes.

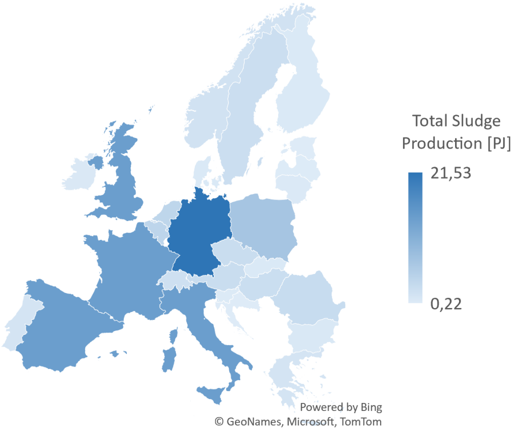


Figure 5.10: Total sewage sludge production in Europe (2020) in PJ

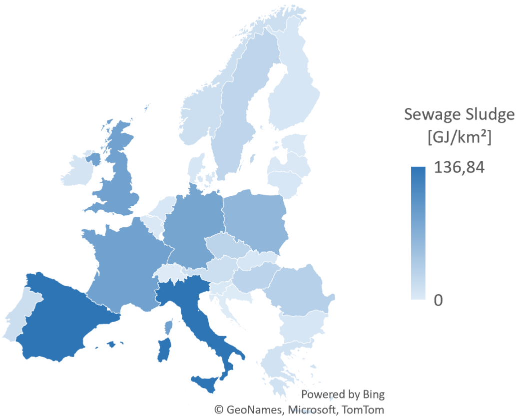


Figure 5.11: Technical sludge available for biofuel use (2020).

5.3. Baseline Biomass Projections

The preceding graphs showed the independent distributions for each type of biomass across all considered countries. However, to gain a deeper insight into biomass availability per country, the relative fractions of biomass types per country will be displayed. This graphic will be useful in the post-processing of the results to further understand why specific biomass types are chosen and why they're pulled from a certain country.

Figure 5.12: Proportion of biomass types by country.

As the figure shows, the feedstocks with the largest proportional availability are forestry and agricultural residues. Southern countries tend to have more potential in agriculture, whereas in general, northern countries have more forestry residues. Livestock wastes make up a considerable portion of total energy potential as well, and are also distributed more evenly throughout Europe. Biowaste and sewage display the least proportional potential.

5.4. Biorefineries

Biorefineries represent a key element in the biofuel production line. They are one of the main possible bottlenecks (capacity constraints) in the supply chain, thus the description of the distribution of biorefineries across Europe (current and future) is necessary. Further, by mapping out the existing biorefineries and later connecting them to feedstock sources and the fuel demand sites, insight into locations of future refineries can be gained.

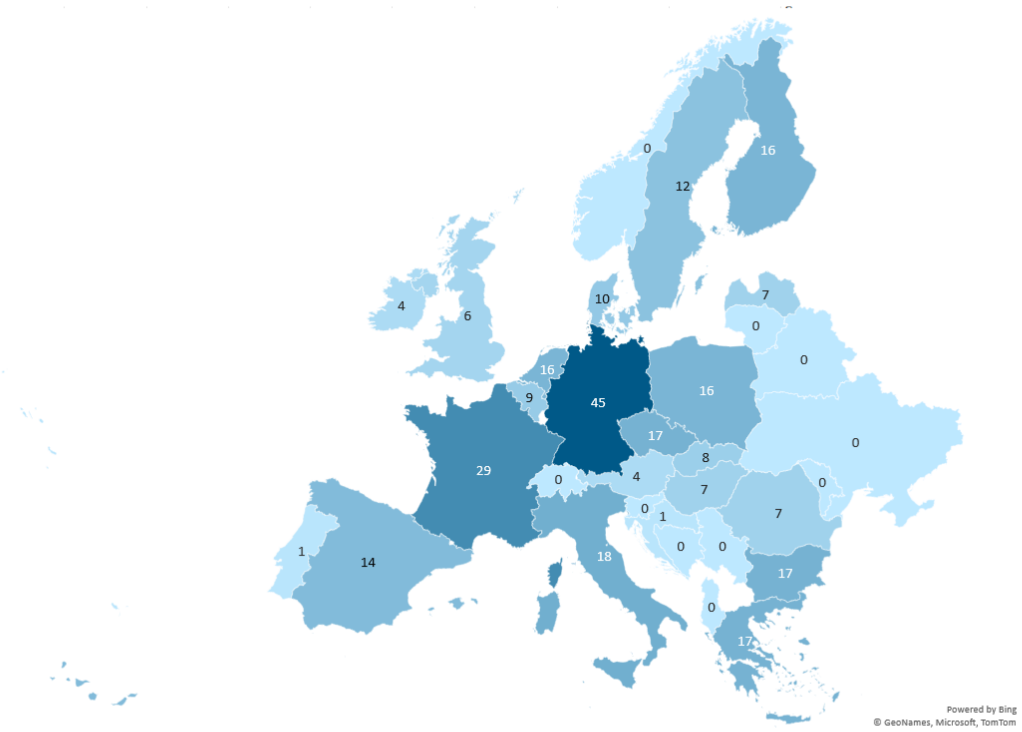


Figure 5.13: Biomethane refineries across Europe in 2019 [8].

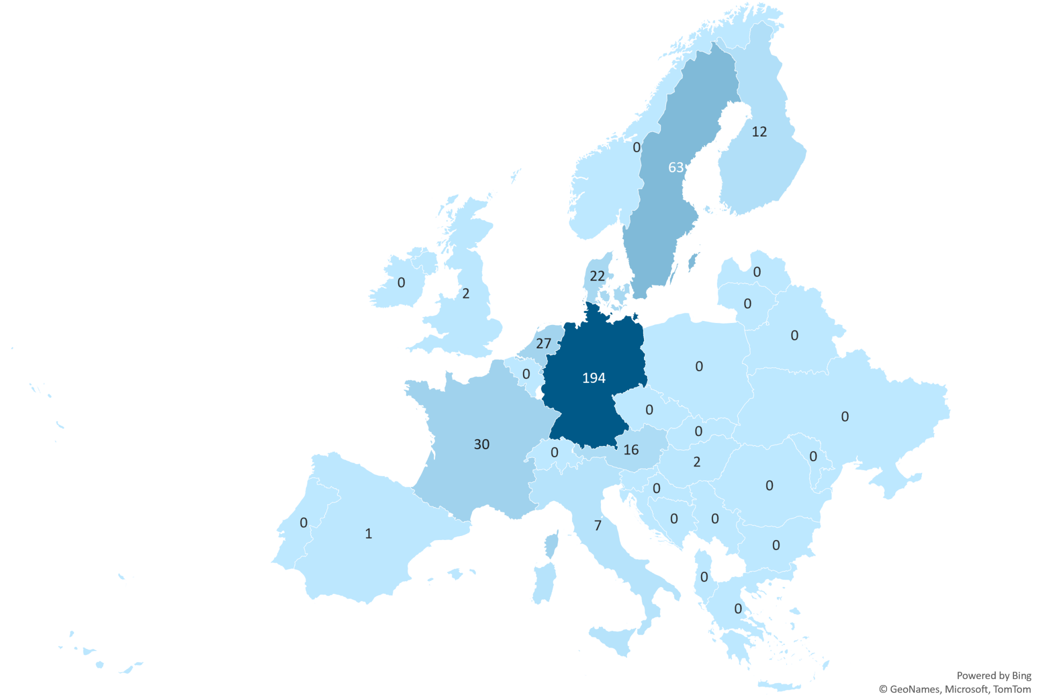


Figure 5.14: Liquid biorefinery distribution across Europe in 2019 [8].

The majority of bio-methane and bio-fuel refineries are found across central Europe, especially in Germany and France. However, liquid fuel biorefineries are more spread out over northern and southern Europe. Two more bio-methane facilities are being planned for construction in Germany and Austria, and are currently in the R&D phase of development. Another 62 biofuel refineries are planned for construction across Europe. The development time associated with each biorefinery depends on the scale and the development phase (i.e. R&D, pilot/demo) [75].

The type of biofuel produced at the refineries depends on the type of plant, and the type of feedstock used. The distribution of feedstock across the biorefineries are displayed in 5.15. Further, around 30% of the refineries use feedstocks from second generation biomass, while 70% are from first [75].

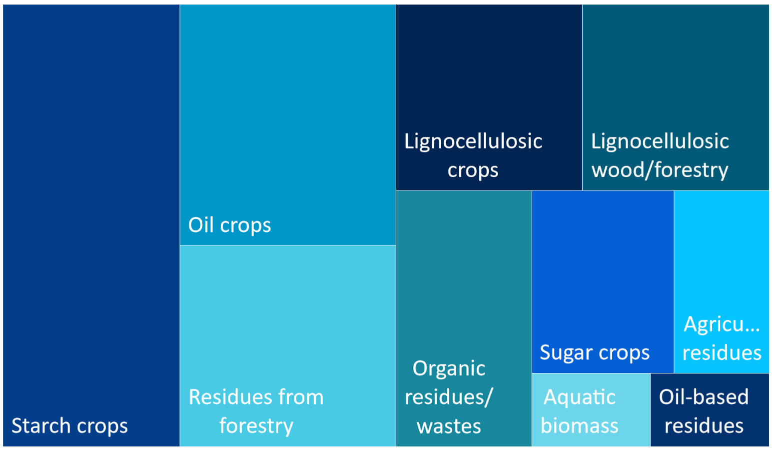


Figure 5.15: Distribution of feedstock types across the in-scope biofuel refineries [8].

Integrated refinery nodes	**Countries**
Rotterdam	Netherlands
Antwerp	Belgium
Hamburg	Norway, Sweden, Demark Germany, Czechia
Bremmerhaven	Norway, Sweden, Demark Germany, Czechia
Valencia	Spain
Athens	Greece, Bulgaria, Romania
Algeciras	Spain
Gioia Tauro	Italy
Felixstowe	United Kingdom
Barcelona	Spain
Le Havre	France
Genoa	Austria, Croatia, Hungary
Southampton	Ireland
Sines	Portugal
Gdansk	Poland, Finland, Latvia, Slovakia

Table 5.2: Assumptions for distribution of country refinery potentials amongst in-scope refinery nodes.

Country	**Pilot/Demo Phase**	**RD Phase**
Austria	4	0
Belgium	3	2
Denmark	5	0
Finland	5	1
France	5	1
Germany	8	2
Greece	1	1
Italy	2	1
Netherlands	5	2
Poland	1	0
Portugal	1	0
Romania	1	0
Slovakia	1	0
Spain	4	1
Sweden	4	0

Table 5.3: Planned bio-refineries [8].

The real-life locations of the considered biorefineries are unevenly spread around the respective country they are located within. However, the exact locations are not know for each plant nor are they required. In an effort to reduce the amount of nodes and steps within the superstructure, an assumption regarding the locations of the biorefineries will be made. In this assumption, only the considered ports are regarded as biorefinery sites. This means that this report only considers 15 integrated biorefineries located at the in-scope ports. The way this can be achieved is by distributing the production capabilities of the real biorefineries amongst the 15 port nodes in a way that is proportional to the local (or surrounding) area. This way, the ports act as both the refining locations as well as the demand sites within the model. Essentially, this will have the effect of reducing the total paths within the superstructure by a factor of 23 (total number of considered countries with some type of fuel producing capacity), which will significantly improve the computational time of the optimization.

The total fuel production capability of a port will reflect the total refining capacity of the biorefineries in its vicinity. The biorefineries are grouped and become part of the port with the nearest land proximity. In other words, the nearest considered port in terms of road distance. Further, the refineres are all assumed to be integrated biorefineries where multiple feedstock can be used to generate various types of products. The total fuel producing capacity of a refinery will be proportional to the number of fuel-specific bio-refineries within the countries assigned to that node, and the average size of bio-methane, bio-ethanol and bio-methanol refineries across Europe, respectively. Table 5.4 shows how countries are grouped and refining capabilities are assigned to ports. For countries multiple in-scope ports, the refining capacities are distributed proportionally amongst the ports with respect to size when data on port size is available, otherwise, the capacities are divided equally.

5.5. Competition

The results presented in section 5.2 identify the theoretical and technical supply potentials for the production of bioenergy. In the process, considerations were made to factor the biomass demand for non-energy applications for each biomass source. However, in order to infer a realistic supply of biomass sources, existing demand for biomass from other energy industries may be relevant. Therefore, two types of biomass demand can be considered, namely, energy and non-energy related.

The non-energy demand is already taken into consideration in the preceding biomass maps of section 5.2. This demand is proportional to the total specific biomass and will remain (constantly proportional to the theoretical supply) through time. The energy demand on the other hand consists of and is subject to changes over time depending on various factors. Positive global population growth is associated with increasing energy demand. This trend, tied in with incentives towards cleaner energy sources has resulted in the expectation of the increase of bioenergy.

Type of biomass	Competing demands	Sustainability constraints
Forest residues	Liquid	No stump extraction Maximum of 70% residue removal to maintain soil quality
Agricultural waste	Animal husbandy Polymers Composting	Maximum of 70% residue removal to maintain soil quality
Municipal solid waste	Land care/fertilizer	n/a
Manure	Land care/fertiliser	n/a
Sewage	Land care Pisciculture	n/a

Table 5.5: Non-energy competition and sustainability constraints for biomass.

Notwithstanding the rapid growth of wind and solar power over the past decade, bioenergy continues to be the main source of renewable energy in the EU, in terms of gross final consumption [76]. The maritime industry will face direct competition from other industries for the procurement and utilization of the available biomass. In order to capture this competition, data on current industry energy use will be compiled and compared using an energy balance. This allows to see the total amount of energy extracted from the environment, transformed and used by end-users. The data analyzed is taken from Eurostat and pertains to the supply, transformation and consumption of renewables and wastes. The main sources of competition and final end users of renewables include the industry sector (i.e. iron and steel, chemical and petrochemical, machinery, construction etc.), the transport sector (road, rail, aviation and domestic navigation) and other sectors including commercial and public services, households, and agriculture/forestry. From the current and past energy use, it is estimated that around 20% of first-generation biomass is available for marine application without any additional competition within (no competition from other maritime fuels or other applications). However, it is not always clear which type of biomass will face competition from each industry and at what level. For example, forestry and agricultural residues are in higher demand for the heating sector, as they can cheaply be pelleted and consumed in the existing heating supply chains. On the other hand, sewage and MSW are not commonly utilized for energy application thus will face lower competitive demand. Assumptions will be made for each class of biomass and the respective competition.

Another aspect that is important to consider in the competition is the type of biomass (in terms of the gen-

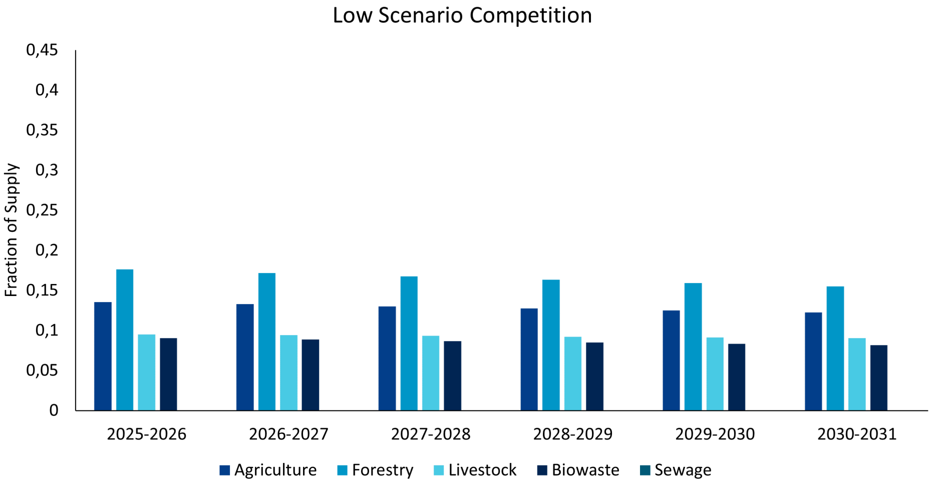


Figure 5.16: Low competition scenario.

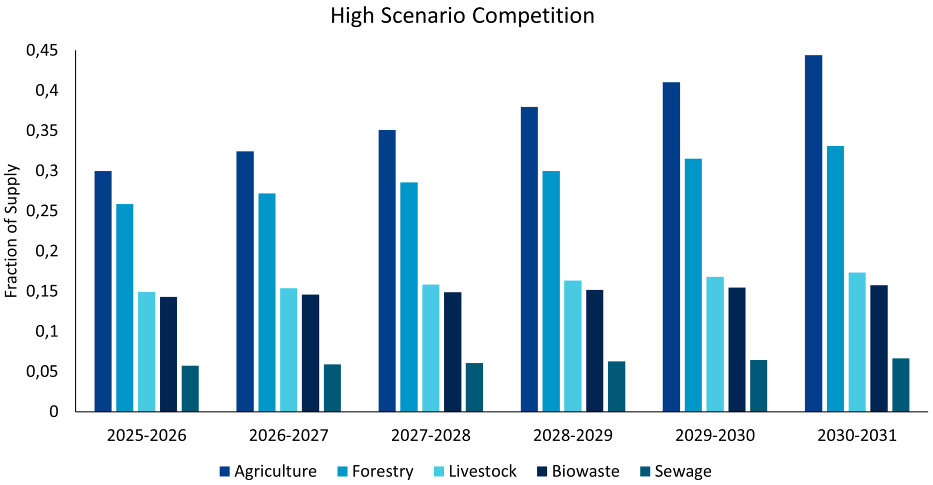


Figure 5.17: High competition scenario

eration). Current biofuel and energy production is centered around first generation biomass, and will slowly shift to second generation sources over time. Third and fourth generation biomass sources could change near-future biomass competition and use depending on their rate of development and adoption. Due to the novelty of the considered biofuels, they might have a competitive advantage over established fuels and energy competitors. The switch from established supply chains might prove to be more difficult than the commencement of new supply chains. To account for the generational difference, a scaling factor in line with the adoption of the technology is applied to the competition. This will be discussed in more depth in chapter 6. It is beyond the scope of this paper to develop a more detailed analysis of the competition in terms of biomass generations. Considerations will mainly be made with respect to other energy industry competition and the class of biomass (i.e. agriculture, sewage, forestry, ect.).

The two graphs (5.16, 5.17) illustrate the low and high competition scenarios. For the low, competition is taken at the current 2020 levels and is set to slightly increase at a linear rate over the coming years. The high competition scenario assumes a larger starting off competition and an exponential increase over the next ten years.

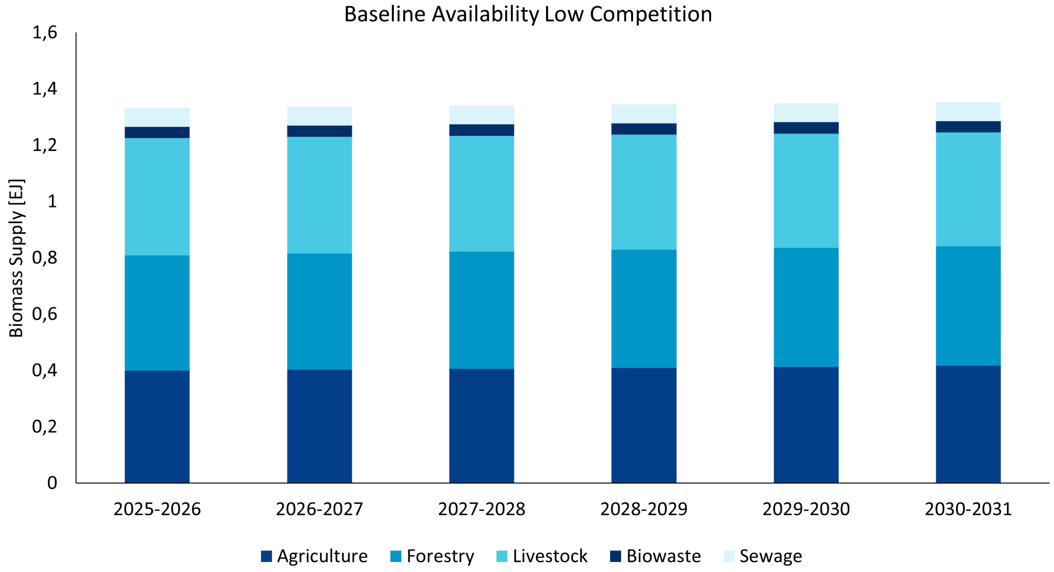


Figure 5.18: Baseline biomass supply scenario (low competition) for all considered countries.

5.6. Biomass Supply Scenarios

After establishing the total baseline supply and competition for biomass in 2020, it is possible to develop the final future supply scenarios. In total, three scenarios will be formed; a baseline availability scenario where the biomass faces low competition, a low availability/high competition scenario, and a low competition/high availability scenario.

In the first scenario, biomass availability follows from the assumptions listed in the preceding sections (5.2.1-5.4) specific to each feedstock. This first scheme serves to provide an idea of the potential of second-generation biomass available for maritime under "normal" conditions (historical rates of growth, no deviation from past trends) and a low competition scenario in line with the current competition of second generation biomass. (There is not enough information and it is outside the scope of this study to determine the actual competition for second generation biomass, thus the competition will be that of first generation in a low scenario).

The second scenario will represent the worst-case situation whereby the availability of biomass will decrease over the next 10 years and be faced with a high level of competition from other industries. This scenario will create a lower limit in terms of what can be expected for the ensuing years. Lastly, the third scenario serves to illustrate the supply case with favorable conditions; low competition and high availability of products. Figures 5.18,5.19 and 5.20 illustrate these scenarios. It can be noted that due to the short timeframe (5 years) of the project, the changes are not substantial throughout the years, and all the trends are linear in nature.

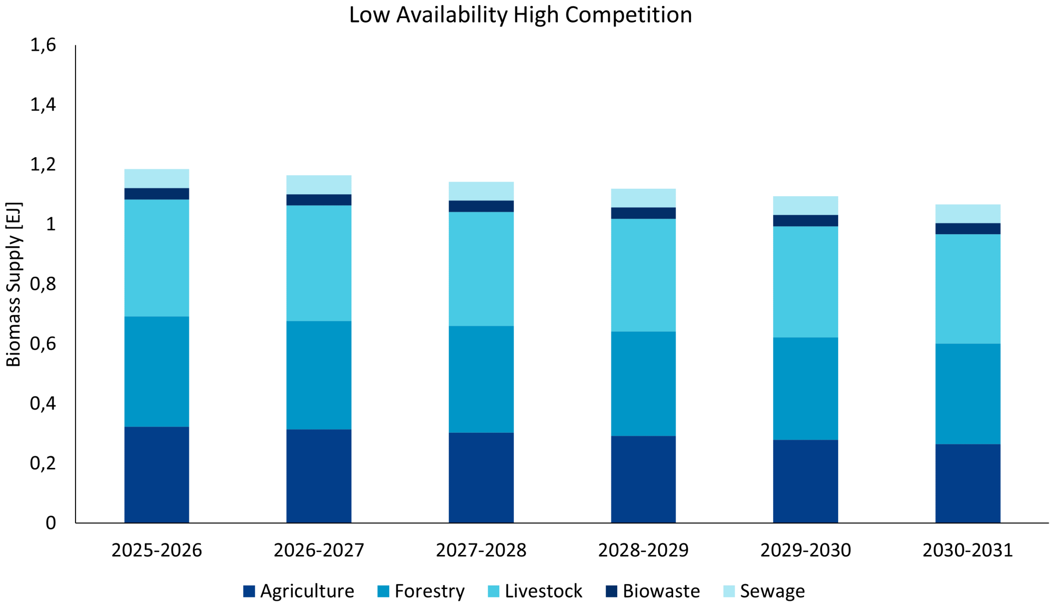


Figure 5.19: High competition biomass supply scenario for all considered countries.

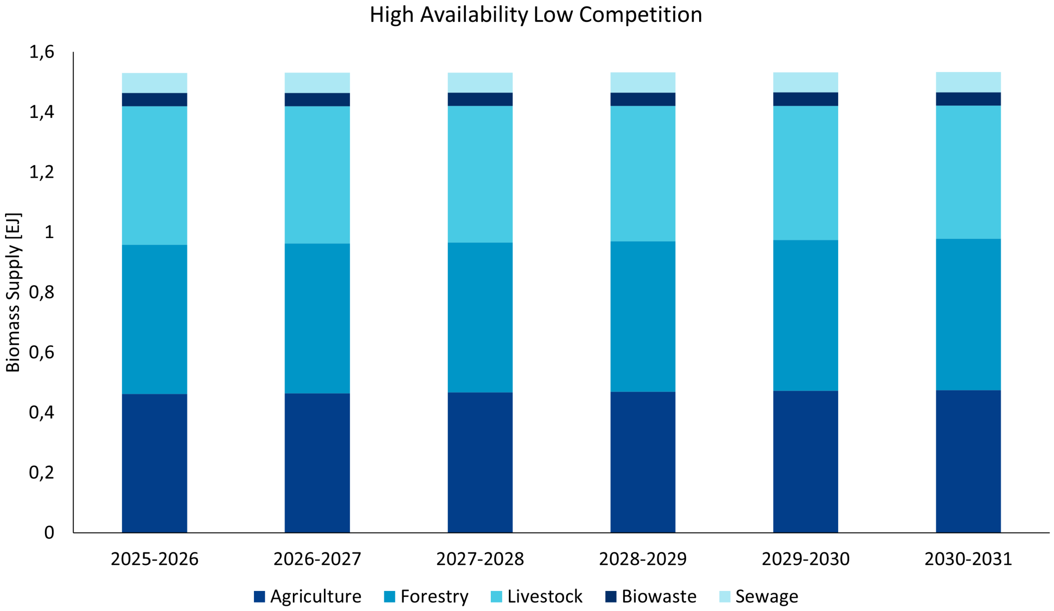


Figure 5.20: Low competition biomass supply scenario for all considered countries.

6

Biofuel Demand

After identifying the potential supply of biomass and biofuels, it is important to consider the demand. Essentially, the demand is the "pull" of the model, describing how much energy is needed and where.

6.1. Key Drivers in Biofuel Markets

Throughout the scientific literature studied, three main drivers are identified for the pursuit of environmentally-friendly innovation. Table 6.1 provides an overview of the drivers that typically lead to the adoption of clean fuels.

Operational drivers or supply side factors	Technology push	• Technological and management capabilities • Collaboration with research institutes, agencies and universities • Access to external information and knowledge • Size
	Cost-Saving	• Material prices • Energy prices
Market drivers or demand side factors	Market Pull	• Market Share • Market demand for green products
Regulatory drivers or environmental policy influences	Regulatory push/pull	• Existing regulation • Expected future regulation • Access to existing subsidies and fiscal incentives

Table 6.1: Key drivers in biofuel markets [13].

In the case of biofuels in the marine industry, the main two initiatives are operational drivers in the form of cost reduction and regulatory policy [13]. The general trend of rising oil prices in combination with the volatility of the market has created a market of new fuels to dampen the effects of crude-oil price uncertainty [26]. Assessing and comparing the costs of advanced biofuels is an objective of this report, however, current and future regulations are uncertain and not binding. The current imposed European mandate from RED II sets the goal of having at least 40% of the EU's gross final energy consumption be renewable by 2030. The Commission's original proposal did not include a transport sub-target, which has been introduced by co-legislators in the final agreement: Member States must require fuel suppliers to supply a minimum of 14% of the energy consumed in road and rail transport by 2030 as renewable energy. Fuels used in the aviation and maritime sectors can opt in to contribute to this 14% transport target but are not subject to an obligation. Although this transport mandate does not include shipping, the RED II also outlines a separate goal in Annex 25 with respect to second-generation/advanced biofuels. Within the 14% transport sub-target, there is a dedicated target for advanced biofuels produced from feedstocks listed in Part A of Annex IX. The contribution of advanced biofuels and biogas produced from the feedstock listed in Part A of Annex IX as a share of final consumption of energy in the transport sector shall be at least 0.2 % in 2022, at least 1 % in 2025 and at least 3.5 % in 2030. Visually, this is the graph of figure 6.1. The mandate also states that contributions of non-food renewable fuels supplied to these sectors will count 1.2 times their energy content and that fuels produced from feedstock from Annex IX

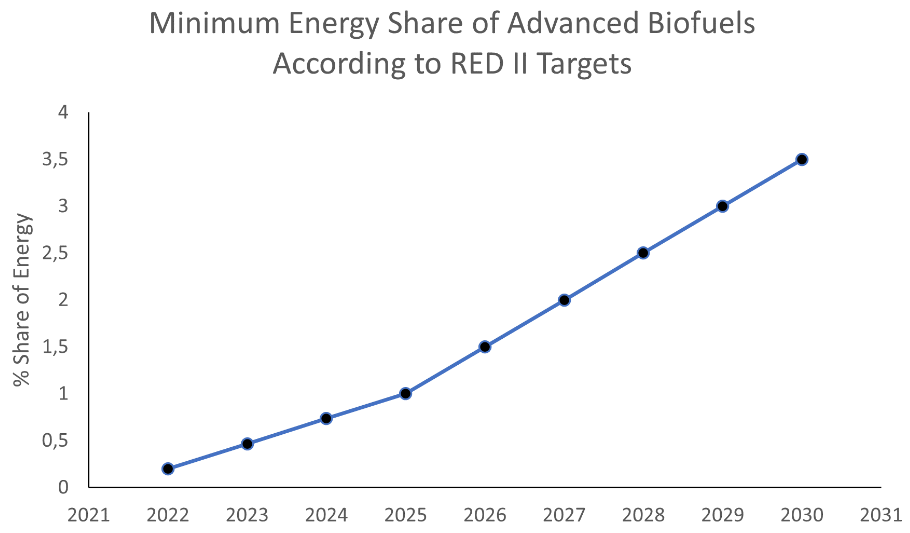


Figure 6.1: Minimum shares of energy from advanced biofuels and biogas produced from feedstock listed in Annex IX [9]

count for twice their energy content. However, since this target is specific to advanced fuels, there will be no double counting nor additional energy considerations with these fuels.

In order to convert this percentage into an amount of energy, the total current and predicted consumed energy in the maritime sector should be calculated. It is assumed that each energy sector complies with the above target and thus only the bunkering energy is relevant for the maritime industry.

6.2. Marine Energy Demand

Marine bunker fuel demand is considered in the IEA's World Energy Model, the OPEC World Energy Model and the EIA's (Energy Information Administration) World Energy Protection Model at both the collective and regional levels. These models estimate the bunker demand though two main approaches; namely a bottom-up and top-down approach. In the bottom-up approach, vessel's attributes such as size, capacity, speed, time travelled, efficiency, among other factors, are used to estimate the amount of fuel used and demanded [77]. This method usually requires large databases and yields results that are slightly higher compared to the top down method. The latter uses information from fuel distribution and production sources themselves such as refineries, port authorities, fuel storage sites and bunkering firms [78]. However, the reporting is not uniform throughout and there are various discrepancies in the collected data. For these reasons, agencies usually perform both a top-down and bottom-up approach. The results from these bunker calculations are usually taken on an aggregate level and then divided into geographical regions using seaborne transportation and trade data [79].

The IMO also publishes a recurrent study on fleet emissions to gain insight into GHG emissions, fleet development, fuel use and bunker demand. The most recent study, the Fourth IMO GHG study 2020 builds on past developments and uses new data to produce more reliable GHG inventories. It is also the first study to distinguish between international and domestic shipping on a voyage basis [77]. The study identifies two main factors in the transport demand projection, namely, the long-term socio-economic scenarios/assumptions underlying the forecast. GDP and population growth are the two main indicators in this, the higher the predicted growth of these two variables, the higher the projected transport work for products that are positively correlated to them. Second, the long-term energy demand scenario. Higher consumption of fuels leads to higher transport work. To account for different recovery scenarios from corona, GDP growth, population change, etc., the latest IMO report has come up with a set of different scenarios that depict multiple future possibilities of worldwide marine energy demand. Three of those scenarios are used in this report as benchmarks for low, medium and high demand cases.

To assess maritime energy demand in Europe per port, the proportion of fuel consumed at European ports is taken as a fraction of total world consumption. As a rough estimate, the share of bunker energy demand in Europe lies between 20 and 25% of all worldwide bunker energy demand depending on the year in question [18]. This figure might seem large, however, a small number of ports account for the majority of the worldwide

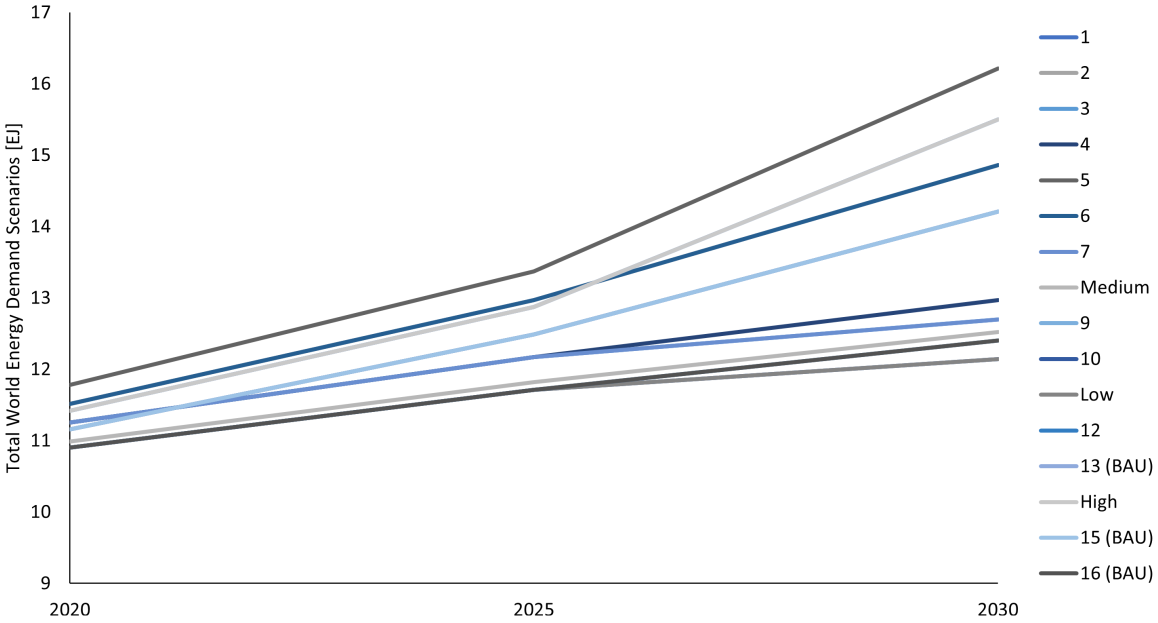


Figure 6.2: Total worldwide energy demand scenario forecast [EJ] []

sales, of which Algeciras, Rotterdam and Antwerp are significant [80].

The OPEC released a World Oil Outlook in 2014 outlining several supply and demand scenarios for the oil industry. In it, key figures were provided on the bunker sales of key worldwide ports [81]. By using a historic approximation of the share of worldwide bunker sales of the main European ports from the IEA [82] and normalizing them with respect to the total European marine energy demand, one can estimate the percentage of bunker energy demand for each of the in-scope ports (with respect to Europe).

6.3. The Marine Fleet

The historical adoption of past technologies and the argumentation of Resenberg on innovation [83] show that the technology demand curve follows a sigmoid nature over time (rather than linear or exponential) with a lower rate of adoption in the first years and a saturation or final level in the later years of adoption. In the long run, with the emergence of newer technologies, the function will reach its maximum and begin its decline. Assuming that biofuels will reach their total potential by 2050 (after which newer technologies will reach a higher usage), their final total adoption should be 30 years from now. The sigmoid function used to reflect this trend can be described by equation 6.1 and reflected graphically through figure 6.3.

$$f(x) = \frac{1}{1 + e^{(c_1 * (x - c_2))}} \tag{6.1}$$

It is anticipated that the uptake of biofuels will be gradual per shipping segment, with the current and future fleet of vessels concentrated in niche or high specification sectors: the RO-PAX and offshore vessel sector have been some of the first adopters of bio-LNG and bio-methanol as fuels [84]. However, another determinant for the adoption of biofuels are the specific routes being travelled. Both the distance and bunkering locations of a vessel will affect its suitability for biofuel propulsion. For example, liner services operating on fixed routes will adopt these newer technologies sooner, as the supply and access to biofuel bunkers can be planned and controlled. Hence, the adoption rates of advanced biofuels is not likely to happen at the same rate for all vessel types, and may not reach the same market saturation for each type of vessel. For example, while 100% of RO-PAX ferries may switch to biofuels by 2050, other vessel types might only reach a fraction of fleet saturation and be phased out for other technologies.

Aronietis et al. [13] developed a forecasting method for determining potential LNG bunker volumes at port level. In the method, the author assigns a different rate of adoption per ship type ranging from "very low" to "very high". Table 6.2 shows the different adoption rates per ship type, largely based on fuel consumption (disregarding any future fuel-saving due to technology improvement) and typical route distance. It is also assumed that the smaller ships will mostly sail in SECA zones and thus will have to use an advanced biofuel in

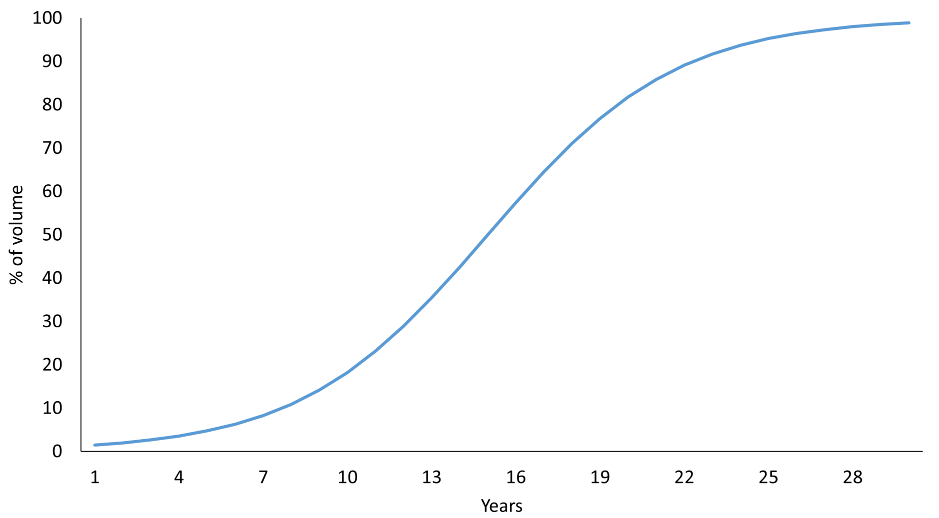


Figure 6.3: Typical sigmoid curve used to reflect adoption rates of technologies.

Ship type	Size	Adooption rate	Possible adoption in 50 years
Small RORO	<180 m	Very high	100 %
Large RORO	180 m	Medium	70 %
Small container	<2000 TEU	High	80 %
Large container	2000 - 8000 TEU	Low	20 %
Very large container	8000 TEU	Low	20 %
Small general cargo	<5000 DWT	High	80 %
Large general cargo	5000 DWT	Medium	60 %
Small tanker	<25000 DWT	High	80 %
Large tanker	25000 - 200000 DWT	Very low	10 %
Small bulk carrier	<35000 DWT	High	80 %
Large bulk carrier	35000 DWT	Low	10 %
VLCC/ULCC	200000 DWT	Very low	5 %
Inland shipping	All sizes	Very low	5 %
Other	All sizes	Medium	50 %

Table 6.2: Adoption rates per ship type in the next 50 years [13].

order to comply with the regulations.

Though the assumed adoption rates in 50 years are beyond the scope of this paper, those figures serve to provide values for fleet biofuel use for the next 10 years, and more specifically the period in question (2025-2030). Again, the main ship types with medium/high biofuel adoption rates will be small to medium sized vessels sailing (relatively) fixed coastal routes. The short distance fleet consists of vessels small enough to travel on narrow waterways such as rivers and lakes, mainly carrying dry and wet bulk cargo. The cargo capacity ranges from 1 to 15 thousand DWT, and accounts for approximately 40% of all freight moved within Europe, with fixed routes which could lend itself to steady biofuel supply in the near-term [18].

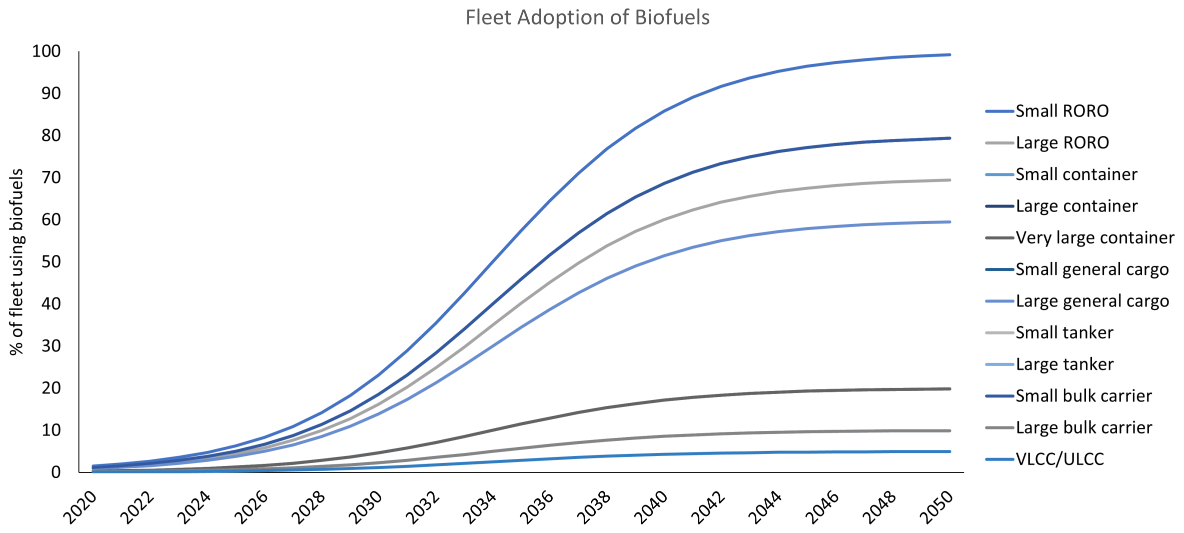


Figure 6.4: Fleet biofuel adoption rate per ship type (long term).

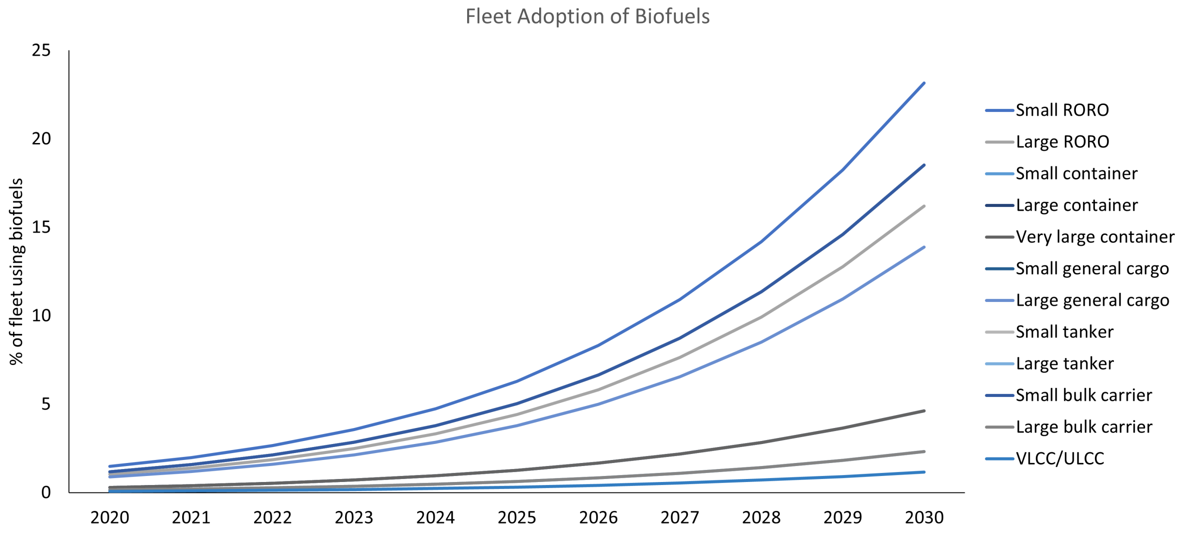


Figure 6.5: Fleet biofuel adoption rate per ship type in medium-term

6.4. European Ports

Ports are the gateways for the international distribution of goods and cargo as well as fuels. Yearly, the number of ports are increasing continually, and modifications need to be done to expand infrastructure and access. Access and availability of marine fuels depends on the port location. Ports with high concentrations of trade will have frequent and regular supply, while seasonal or small ports do not have the adequate infrastructure to supply fuel continuously, and thus encounter irregular access to marine fuels. Ports which are close to large populations and large manufacturing centers tend to have the most developed infrastructure and highest demand [27].

It is difficult to assess the specific capabilities of each port and the specific share/types of bunker vessels as most ports do not publish this data. However, it can be assumed that the majority of biofuel bunkering will take place in ports where conventional fuel bunkering is already large and established. For example, Rotterdam, as Europe's largest port has established rail, truck, and coastal shipping connections as well as on-site oil and chemical refineries with a capacity to store one million square meters of crude oil and other chemicals [27]. Further, the port has partnered with a number of companies including Goodfuels since 2015 to give ships the option to sail of biofuels. Following the criteria of Rotterdam, the largest bunkering ports across Europe are chosen to represent the main providers of biofuels and bunkering services now and in the near future.

6.5. Marine Biofuel Demand

With the energy demand in mind, and applying the percentages of advanced biofuels to meet the outlined targets, three marine biofuel demands can be obtained; a low, a medium and a high scenario. Table 6.4 describes what parameters are used in each.

Table 6.3: Marine biofuel demand scenario considerations.

	Low	**Medium**	**High**
European Energy Demand	OPEC World Oil Outlook: Low Energy Consumption	OPEC World Oil Outlook: Medium Energy Consumption~	OPEC World Oil Outlook: High Energy Consumption~
Energy Share of Biofuels	RED II advanced biofuel target	RED II advanced biofuel target	2x RED II advanced biofuel target

Table 6.4: Different demand scenarios.

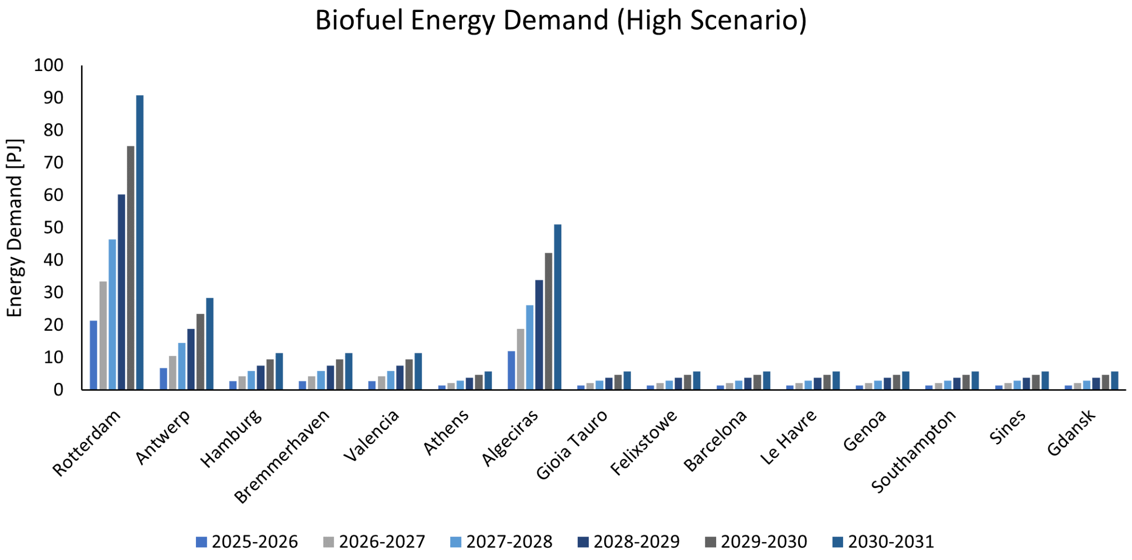


Figure 6.6: High demand scenario.

All of the presented scenarios assume that biofuels will meet the RED II advanced biofuel targets. The differences in energy demand based on the OPEC World Oil Outline scenarios are marginal, largely due to

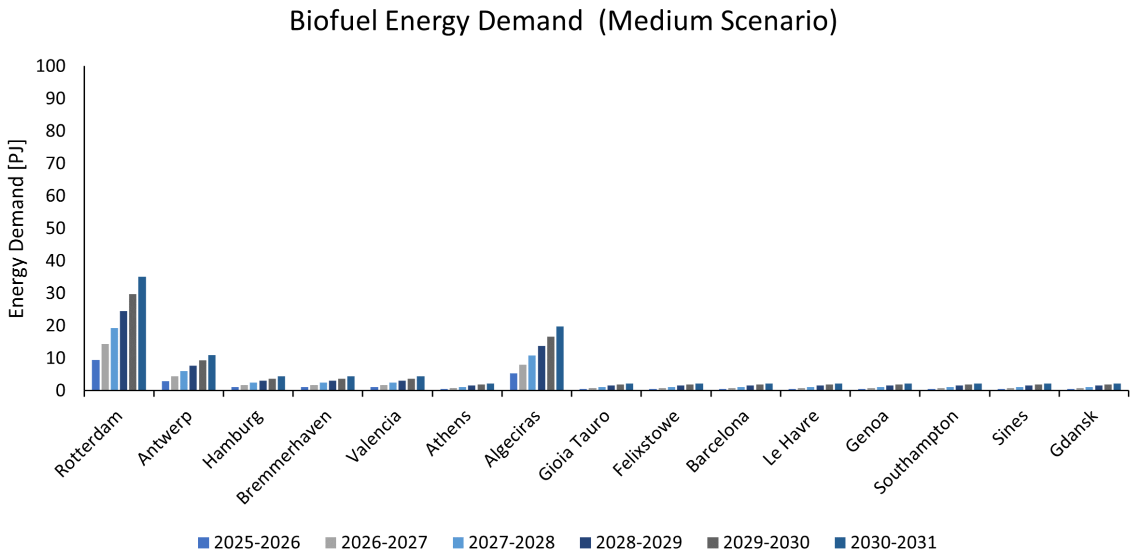


Figure 6.7: Medium demand scenario.

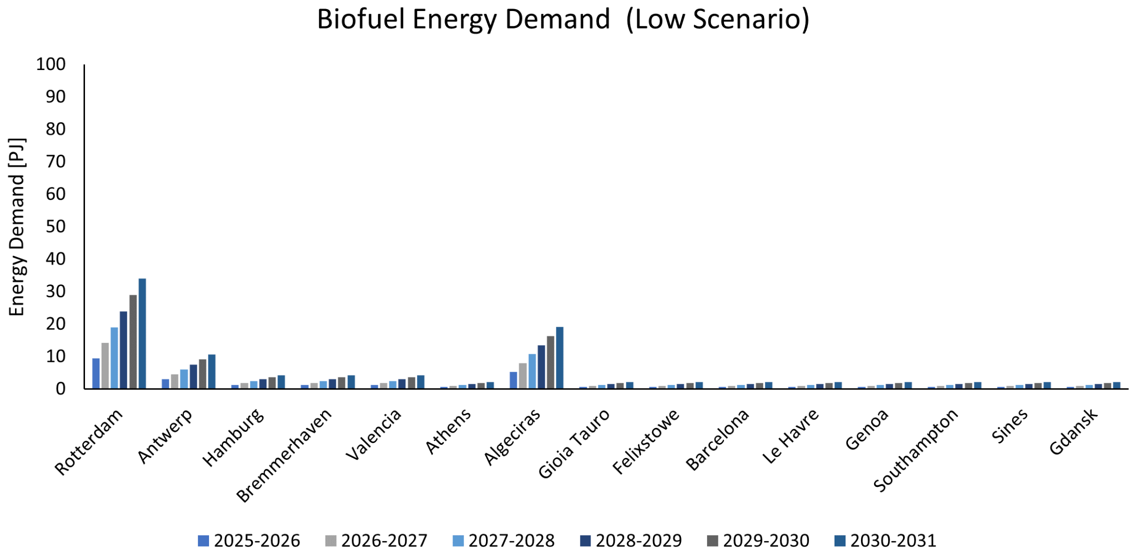


Figure 6.8: Low demand scenario.

the short time-frame (in the long-run small approximations manifest into large deviations). This can be seen between the low and medium demand cases, which are very similar. For this reason, to gain a larger range of demand cases, the high scenario is based on twice the RED II advanced biofuel share targets. It is unrealistic that emission targets/regulations are loosened up in the future; the only probable deviation is a tightening of current objectives. However, there could be some delays in what is achievable for a certain number of reasons. The low scenario reflects a lowering of energy demand in-line with a delayed economic recovery from the pandemic on the global economy. The key variable that changes in this scenario is the rate of economic growth, which in turn affects the industrial output, sales, shipments, and trade.

The medium case creates a picture of the business-as-usual with the current objectives and economic growth levels. The final high demand case combines a steep economic growth due to an accelerated "bounce-back" from the covid recession with a tightening of emission goals. This scenario is much higher than the other two and serves as a ceiling in terms of what can be expected in advanced biofuel demand for the in-scope period.

7

Costs, Emissions and Other Parameters

The mathematical model developed in chapter 4 described the modelling environment through a set of economic, environmental and miscellaneous parameters. These parameters were chosen and calculated in such a way to represent real-life conditions as accurately as possible (given the project timespan, data availability and other restrictions). The rationalization and visualization of the important data are provided in this chapter.

Starting with the costs and then emissions and other parameters, each constant used in the model is explained below to create a more comprehensive understanding of the mathematical model and the assumptions used.

7.1. Costs

7.1.1. Feedstock Costs

Feedstock costs are defined as the product of the total amount of biomass used (expressed in GJ) and the unit biomass cost (in €/GJ)

The cost assessment of the feedstocks follows a pragmatic approach and a distintion is made between different types of costs and price estimates for a specific biomass type. Market prices for already traded biomass types can easily be found in data libraries. On the other hand, prices for biomass which markets are essentially undeveloped (currently) have to be reasoned. The majority of the biomass sources being considered fall into the second category.

Future prices (from 2020 to 2030) are presented in real price levels, so no inflation rate correction is applied. Furthermore, all feedstock cost are expected to decline by 10% within the next 10 years due to technological learning and increase in efficiencies. Feedstock prices for 2020 per country can be found in Appendix C.

Agricultural Residues

Straw and stover are commodities that are sold in national and international markets. There are published reports (mainly on renewables and biomass energy) and seller data indicating country specific price ranges for these commodities. Costs of other residues such as shells and stubble are not as established or available. To overcome this, prices for all lignocellulosic agricultural residues are taken to be the same as straw/stover (in terms of cost per energy content). For each country, the data is methodologically collected as well as price bounds (maximum and minimums) to assess the average prices. For countries where data is not publicly available, prices from similar countries is taken.

Manure

For the manure cost estimation, a separation is made between liquid manure (originating from swine) and solid manure. The price of liquid manure is set at zero and the solid manure receives a price reflecting the market price of solid fertilizers. The reasoning behind this is that most of the liquid manure produced on a farm is either used as fertilizer or as a source of energy (through digestate) [85]. Since liquid manure is more costly to transport, it is used up first at the farm for various purposes. Therefore, when liquid manure is transported from the farm, it usually means there is an excess of manure at farm level, which according to the "Nitrate Directive" means it is the farmer's responsibility to get rid of it [86]. On the other hand, solid manure is easier

Country	Methodology (Price)
Romania	Same as Croatia
Sweden	Same as Denmark
Slovenia	Same as Croatia
Italy	Same as Croatia
Lithuania	Same as Poland
Latvia	Same as Poland
Estonia	Same as Poland
Bulgaria	Same as Croatia

to collect and cheaper to transport, and is therefore attractive as a market commodity. Solid manure prices are taken from several sources and then extrapolated to give estimates for countries where data is not available.

$$C_M = \frac{\text{Solid Manure Produced in Country s}}{\text{Total Manure Produced in Country s}} * c_s^m * \frac{1}{LHV} \tag{7.1}$$

The cost of manure per energy content in a certain country can be expressed as the fraction of solid manure produced times the cost of solid manure (per ton) divided by the weighted average of the lower heating values (pertaining to the different animal wastes).

Forestry Residues

Forest products such as saw logs, firewood, pellets and chips are well developed commodities, prices for these can be obtained at a national level. However, prices vary and fluctuate heavily depending on the year and also as a result of negotiations between consumer/sellers, thus it's not straightforward to determine a price level that reflects an entire country. Country prices are therefore averaged, and relative price level indices are used to estimate values for countries where data is not available/straightforward. Although, this comparison is usually done for commodities that are trade-able and have some type of quality standard making them suitable for conversion, it is assumed that by 2025, the market for second generation biomass will be established enough for this comparison to be relevant.

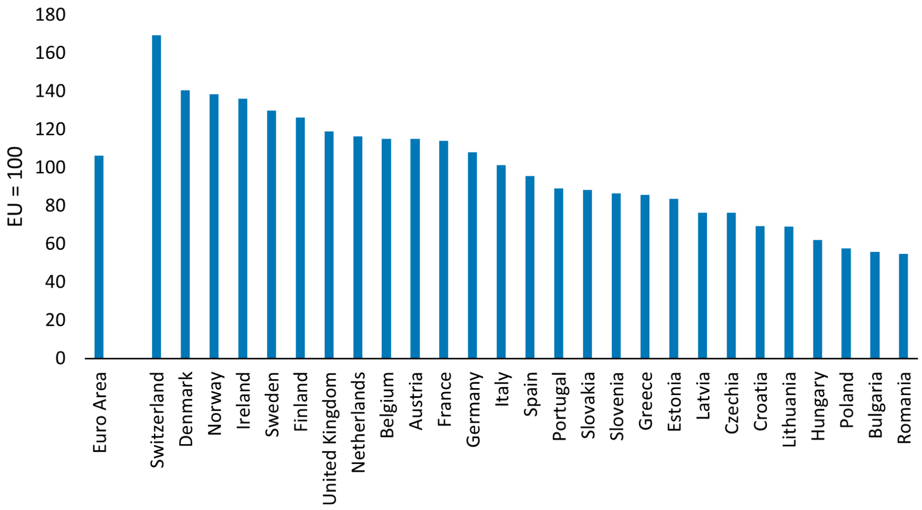


Figure 7.1: Relative Price Levels.

MSW and Sewage

Municipal solid waste and sewage are both waste products that are produced at no cost. Current policy instruments across Europe have seen the reduction of waste disposal in landfill sites [87]. Many countries have gone as far as adding landfill taxes per ton of dumped waste. The same is true for sewage sludge, which also brings forth high treatment costs for traditional disposal methods. The costs for these two products are assumed to be zero.

7.1.2. Collection Costs

The collection costs can be though of as the costs associated with loading biomass onto trucks and the extra costs of separation. The basic parameters involved are the labour costs, diesel prices, the productivity of labour and the productivity of the feedstocks.

It is assumed that for the considered feedstocks, there are no costs associated with "harvesting". For MSW, sewage, forest and agricultural waste, it is taken for granted that the products (garbage, wastewater, wood/trees and crops, respectively) are first collected and then the primary product is separated from the residue or waste product. This collection process comes at no additional cost to the supplier. The animal wastes considered in this thesis outline the total amount of available animals in Europe, of which a large percentage are pasture raised or simply lack the infrastructure for cost-free collection. In practice, three main collection systems are usually employed (scrape, flush, and auto scrape) that incorporate the use of a tractor, water, and stationary scraping mechanism (gutter system), respectively, to remove wastes [88]. To account this, the collection of animal wastes will incur additional costs and will be assumed to be done by tractor.

During the loading phase, all products are assumed to be loaded onto transport trucks using front wheel loaders with 3.5 m^3 bucket capacities, allowing for a loading rate of 5.5 m^3/min. The costs associated with loading the products include the labour, fuel and rental costs of the loaders. For the machinery rental, rates from Germany and Austria were taken as a reference. The price level index was again used to calculate the rates in other countries. This is divided by the productivity of labor (figure 7.2) of the respective country to reflect the output per labor hour. This factor also reflects differences in physical capital, technologies, and education/specialization in the workforce between the countries.

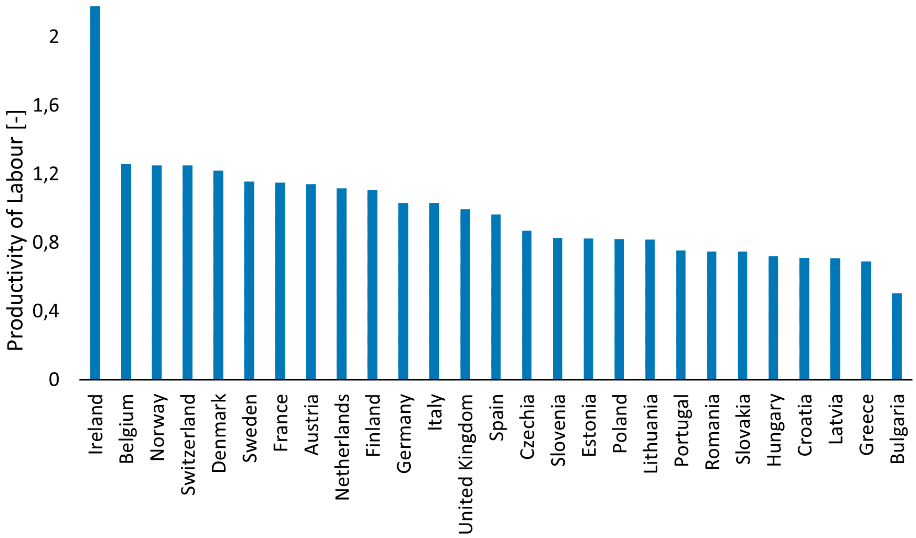


Figure 7.2: Productivity of labor (EU27 2020 = 100) [11]

$$\beta_l^{-1} \cdot r^{-1} \cdot (w_{s,t} + rc_{s,t} + cft_{s,t} \cdot fc^{loader}) \cdot \rho_b^{-1} \cdot \left(\frac{1}{LHV_b}\right) \cdot BU_{b,s,t} \tag{7.2}$$

The rental costs of the loader are calculated by using an average of hourly rental rates in Germany and multiplying that value by a country's normalized price level (with respect to Germany).

7.1.3. Pre-Treatment Costs

As explained in earlier chapters, the treatment considered in the pretreatment phase deals only with densification and physical alteration of the feedstocks. It is not possible to identify stand-alone pretreatment systems without considering the conversion pathway, as these are always part of a larger processing concept for producing fuels/chemicals. All biorefineries considered in this report are integrated systems, whereby the unaltered (in terms of chemical processes) product enters and the final product is the yield. Therefore, the main purpose of the pretreatment phase as described in this thesis, is to densify feedstocks within the origin country for the reduction of transportation and handling costs along the supply chain.

The pretreatment process includes a drying process to remove moisture. The simplest form of drying is

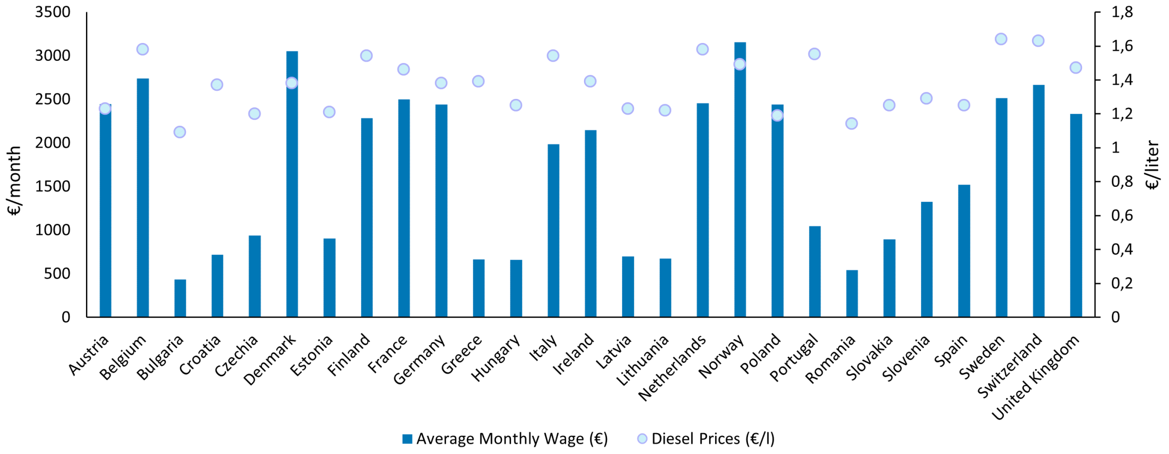


Figure 7.3: Average monthly wages (left axis) and diesel prices (right axis) in each country

field drying (passive drying), which essentially is free. In contrast, active drying makes use of energy to reduce moisture. The specific energy required to dry out biomass depends on a multitude of factors. Several studies have looked into biomass drying methods. One particular study by J. Tumuluru demonstrated the effects of moisture content on energy consumption for the drying process of poplar, black locust, and grapevine prunings in a rotary drier [89]. Specific energy consumption values for different feedstocks and distinct moisture content levels were collected and linerly regressed for each feedstock to estimate the specific energy consumption for drying a feedstock of a certain moisture content.

Size reduction, or comminution, is also an essential component of biomass logistics as downstream conversion prefers a specific in-feed particle size. Additionally, breaking down the feedstock aids in downstream handling and transportation by increased load density and flowability. The process can be conducted with either chippers (use knives to cut and shear) or grinders (smash/crush). In general, the type of material dictates the type of comminution equipment to use. Due to the nature of the utilized feedstocks, chippers are the more suitable option. [90]. A study by Moiceanu et al. [91] illustrated a comparative analysis of experimental results obtained by grinding and chipping multiple types of biomass for the process of bio-refining. Key findings in the study however, were the necessary grinding power and specific energy consumption for different types of dried biomass at differing revolution speeds and particle sizes. In another study, Liu, Wang and Wolcott assessed the specific energy consumption and physical properties of comminuted biomass for bioconversion [92]. Liu found that the measured SEC depends on various variables including MC, original feedstock size, biomass type, screen size, grinding mechanism and other operational parameters. The experiments showed that a reduced moisture content along with using the right processing method significantly lowered the SEC. For this reason, the drying process is done beforehand. Specific energy consumption for the commutation process ranged from 1.26 to 2.7 MJ/kg depending on the feedstock for equivalent particle sizes at zero moisture contents.

Each size reduction/moisture removal process encounters biomass loss which has a double cost associated with the process. First, the lost material must be counteracted by collecting additional biomass to make up for the loss. Second, all costs prior to the loss are lost, thus any losses late in the supply chain can have significant economic impacts. For instance, encountering a 5% loss of material at the biorefinery will mean that the separation, loading, pretreatment and transportation costs will be lost for that portion of the material. This biomass loss in the pretreatment phase is captured through the variables δ^{drying} and $\delta_{milling}$ for each treatment application.

$$BU_{s,b,t} \cdot ce_{s,t} \cdot \left(\frac{sec_b^{drying}}{LHV_b^{wet}} + \frac{\delta^{drying} \cdot sec_b^{milling}}{LHV_b^{dry}} \right) \tag{7.3}$$

The factor $ec_{s,t}$ which is responsible for determining both the costs of pretreatment and conversion, is the respective national price of electricity. The average rates for non-household consumers were retrieved from Eurostat. The rates presented in 7.4 exclude all taxes and apply to the IB Band which include industry users that consume between 500 and 2000 MWh yearly.

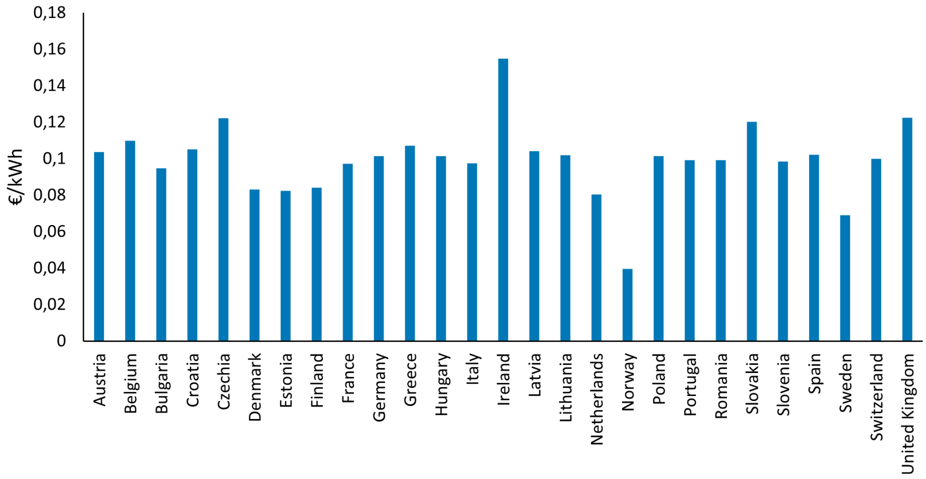


Figure 7.4: Electricity prices for non-household consumers in Europe [11]

7.1.4. Refinery Conversion Costs

For the conversion of pretreated biomass into the final fuel, an estimation is made for each biomass and fuel pathway. Several sources with a biofuel cost breakdown were collected and compared to determine the most realistic prices. The different sources breakdown the costs at different levels and in different countries. To overcome these differences, only the operational costs are considered. Capital investments are not part of the analysis, as the biorefineries considered are already operational or will be (regardless) within the specified period. Further, no distiction is made between costs of processing in different ports. It is assumed that all port refineries have the same infrastructure and costs across all of Europe. This assumption is made because there are not enough country-specific sources on biorefinery costs in europe available to make an accurate depiction. Further, the differences in costs depend on more than just country-specific indicators such as the price level or the local wage.

Depending on the type of plant, the operational costs can include personelle costs, maintenance costs, costs of consumables and waste products as well as some miscellaneous costs, which are all needed and part of the conversion costs. The operational costs of the biorefineries considered in this thesis are proportional to the operational costs of biorefineries found in literature. To account for the plant size differences between the ones in this thesis and the ones found in literature, the operational costs c_{ope} are found using the reference plant size P_{ref}, and a scaling factor, SF. The scaling factor exists because the costs involved in a conversion plant are not linearly proportional to size. The relationship can be better described as exponential, as refineries tend to become more efficient with size and thus become exponentially cheaper with increasing scale. The scaling factors are taken from [93] and range from 0.40 to 0.80 depending on the reference biorefinery size and type.

$$C_{\text{ope},j} = C_{\text{ope ref, }j,}\left(\frac{P}{P_{\text{ref}}}\right)^{SF_j} \tag{7.4}$$

For refineries where the operational costs are expressed with respect to the annual operating hours, the specific operating costs are calculated by dividing by the plant size and the total yearly full-load hours, FLH. It is assumed that the plants are in operation 4500 hours yearly.

$$c_{\text{ope, }j} = \frac{C_{\text{ope, }j}}{P \cdot \text{FLH}} \tag{7.5}$$

7.1.5. Transportation Costs

Transportation costs include all costs associated with hauling primary, intermediate and final products. The transport costs were divided into three parts. In the first leg of transport, countries were modelled as circular areas with sizes equal to their real respective areas. The first distance to be travelled in each country (the average distance between a biomass collection site and a pretreatment facility) is 50% of its corresponding radius. This makes the assumption that all pre-treatment sites located in a country are within one fourth of the largest (estimated) distance in that country, which seems to be a reasonable assumption. This might, however, be an overestimation, as for multiple feedstocks (i.e. forestry), pretreatment is done on site. Therefore, this value will later be tweaked in a sensitivity analysis to understand the effects of this assumption. This distance is multiplied by the diesel cost of a transport truck (per kilometer). Finally, this is multiplied by the total amount of trucks needed to transport all biomass, which can be expressed as the total biomass type b used (in terms of energy) divided by the specific energy capacity of a truck per biomass type.

The second and third transport legs are calculated in a similar way. In the second leg, a distinction is made between LHV_b^{wet} and LHV_b^{dry} to highlight the separate transport capacities between biomass and intermediate products. Since the product being transported has gone through a pretreatment, a larger energy content can now be carried by trucks. In the last transport leg, the LHV of the fuels being transported are used. The costs of shipping the fuels are goverened by the chartering rate of the vessel being used. It is assumed the vessels travel at a speed of 17 knots, which is appropiate for a short-sea tanker vessel. The vessel is further assumed to be a coastal chemical tanker with a DWT of 25,000.

The distances between the countries and the ports are calculated by using a Google Maps API configuration with Excel to get realistic road distances between the nodes. The point location of a country is considered to be the geometric center of the country as defined by Google Maps. A similar approach is used to calculate all the nautical distances between all ports (using a nautical distance calculator).

7.2. Emissions

To explain the methodology used for the calculation of the supply chain emissions, it is first useful to explain how the RED II directive outlines the rules for the calculation of the greenhouse gas impact of biofuels. Annex IV states that "greenhouse gas emissions from the production and use of biofuels shall be calculated as:"

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} \tag{7.6}$$

Where:

E = total emissions from the use of the fuel
e_{ec} = emissions from the extraction or cultivation of the raw material
e_l = annualized emissions from carbon stock changes caused by land-use change
e_p = emissions from processing
e_{td} = emissions from transport and distribution
e_u = emissions from the fuel in use
e_{sca} = emissions savings from soil carbon accumulation via improved agricultural management
e_{ccs} = emission savings CO_2 capture and geological storage
e_{ccr} = emission savings from CO_2 capture and replacement

This equation, however, was simplified in line with the scope of the project. To start, the emissions from the fuel in use are excluded. The objective of this study is to assess the emissions related to the supply chain of the fuels. The emission profiles of these fuels are well documented and know (which is why they have been recommended as potential transitional fuels), thus these are outside the scope of the study. Typically, energy system models only consider direct energy-related emissions. Therefore, biomass cultivation and harvesting are considered carbon-neutral from an energy system perspective. Further, any emission savings are also excluded due to the fact that these values are uncertain and difficult to measure, also they would only apply to forestry and agricultural residues. Obtaining these values from any source outside of the RED II could lead to wrong/unrealistic results. The outcome of this decision is a slight overestimation of the total emissions as defined by RED II. Lastly, any emissions related to direct/indirect land use change are disregarded. All considered products are byproducts/wastes and thus do not contribute to ILUC. The terms that remain are the emissions from extraction, processing and transport/distribution.

The directive further states that all emissions should be measured by their carbon dioxide equivalent, which is a metric used to compare emissions from various greenhouse gases on the basis of their global-warming potential (GWP). By converting amounts of other gases to the equivalent amount of carbon dioxide, different green house gasses can be compared.

7.3. Cost of Emissions

For a multi-objective optimization, there is always a trade-off between the objectives and thus, both objective functions must be comparable on a unit basis. For this to hold, the emissions must be transformed into a monetary basis so that they can be compared to the costs. A good way of doing this is by relating emissions to the EU-wide tax per ton of emitted CO_2 [94], otherwise known as the cost of CO_2. On 14 July 2021, the European Commission adopted a series of legislative proposals setting out how it intends to achieve climate neutrality in the EU by 2050, including the intermediate target of an at least 55% net reduction in greenhouse gas emissions by 2030. The package proposes to revise several pieces of EU climate legislation, including the EU ETS (Emission Trading System), which applies to all EU and EEA-EFTA states [95]. Historically, the carbon tax has been subject to change and in recent months has seen a significant increase up to the current value of 62€per ton of emitted CO_2. Figure 7.5 shows the trend in the last months.

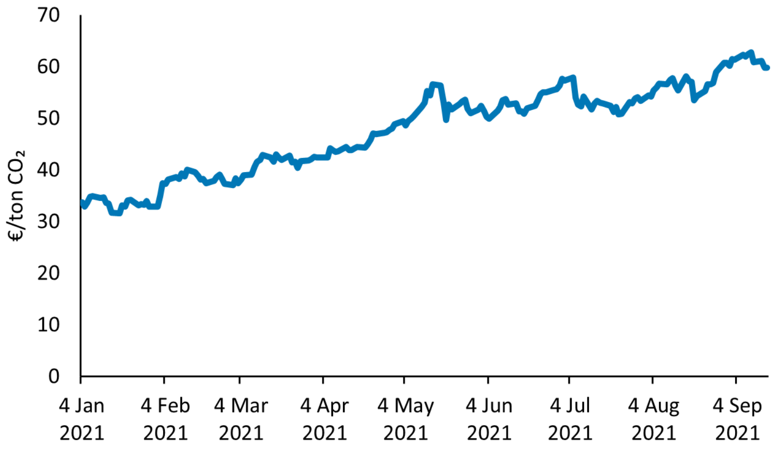


Figure 7.5: Historic EU ETS carbon tax price [12].

Despite the recent spike in price, multiple sources claim that future projections are unlikely to continue this trend. Instead, differing sources predict that the price could be anywhere from 30 to 130 $€/tonCO_2$ by 2030 [96, 97]. In this report it is assumed that the carbon tax will follow a linear trajectory from its current price to the predicted price of 90€in 2030.

7.3.1. Emissions Related to Biomass Extraction & Collection

The first factor that appears in the emission equations is efc_b which in RED II is expressed as e_{ec} and depends on the type of biomass being collected. These values are expressed in RED II as unit CO_2eq/MJ. The directive states that the emissions from the extraction or cultivation of raw materials "shall include emissions from the extraction or cultivation process itself; from the collection, drying and storage of raw materials; from waste and leakages; and from the production of chemicals or products used in extraction or cultivation." Thus it is safe to say that by using the metrics and values provided in RED II, the calculation of emissions will not be lacking.

Emissions per dry-MJ of feedstock are calculated first by dividing the respective CO_2eq/MJ of fuel by the fuel feedstock factor and the fuel allocation factor.

$$\mathrm{e_{ec}feedstock}\left[\frac{\mathrm{gCO_2eq}}{\mathrm{MJfeedstock}}\right] = \frac{e_{ec}\mathrm{fuel}\left[\frac{\mathrm{gCO_2eq}}{\mathrm{MJfuel}}\right]_{\mathrm{ec}}}{\text{Fuel feedstock factor} \times \text{Allocation factor fuel}} \tag{7.7}$$

Where

$$\text{Allocation factor fuel } = \left[\frac{\text{Energy in fuel}}{\text{Energy fuel + Energy in co-products}}\right] \tag{7.8}$$

and

$$\text{Fuel feedstock factor } = [\text{ Ratio of MJ feedstock required to make 1MJ fuel }] \tag{7.9}$$

However, for all feedstock in question, the directive states that e_{ec}fuel is equal to zero since they all originate from waste sources. While a practical assumption for the purpose of giving preference to second generation biomass over first generation (in terms of total emissions), this rule is not entirely accurate. As in the case of the collection cost calculations, machinery is involved in loading the respective biomass onto trucks. Thus, the emissions associated with the collection will be those of the machinery involved in loading the biomass onto trucks.

$$\frac{BU_{s,b,t} \cdot fc \cdot eff^{d}}{LHV_{b}^{wet} \cdot \rho_{b}^{wet} \cdot r^{loader}} \tag{7.10}$$

Where rho is the density of the material, cap the capacity (expressed in m^3), r, the rate of loading, fc, the fuel consumption an eff^d the emissions related to the combustion of 1 liter of diesel.

7.3.2. Emissions From Processing

Again, for the processing emissions, the RED II is used as a reference and guide. According to the mandate, processing emissions include all emissions from the processing itself including waste and leakages, and from the production of chemicals or products used in processing, including emissions from fossil inputs. This also includes emissions from comminution and drying from the pretreatment phase. RED II only includes processing emission values for more traditional fuel types, thus, for the three fuels, values have to be pulled from literature.

For any electricity use related emissions, the RED II states that "To ensure that re-newable fuels of non-biological origin contribute to greenhouse gas reduction, the electricity used for the fuel production should be of renewable origin." Therefore, the emission factor (or unit emission) from the use of electricity in the processing steps shall be assumed to be that of renewable electricity.

7.3.3. Emissions from Transportation

The emissions from transportation are calculated as the emissions from the fuel in use during transportation. For the inland transportation, trucks are assumed to carry all raw and intermediary products. The equivalent CO_2 emissions of one liter of diesel are assumed to be 2.64 $kgCO_2$. The marine fuel emissions are estimated on the basis that the bunkers are consuming the same type of fuel they are transporting. Aside from LNG, the fuel consumption and bunkering prices of the fuels are not well established. Even for LNG though, prices are extremely volatile and unpredictable.

7.4. Miscellaneous Parameters

Though costs and emissions are the two types of values that have direct influence on the objective functions, these are also grounded on several other parameters.

7.4.1. Conversion Yields

The fuel feedstock factor is a way of describing the efficiency of a process, or in other words, the fuel yield from an amount of feedstock. The yield depends on the type of fuel and feedstock. On top of this, there are a great deal of parameters that affect the value of this factor such as the moisture content, volatile material mass, etc. For example, a study by Zou, Malten et al. compared sugar yields in high solids hydrolysis of biomass and showed the variability of the actual yield depending on the substrate used, the mass fraction of insoluble solids in total solids, the mass fraction of total solids in slurry, the enzyme dosage and the hydrolysis time [98]. Results varied significantly (more than 20%) just by altering one parameter. On top of this, technology developers rarely publish real data on biomass conversion yields, and scientific papers rarely have access to performance data on large-scale plants. Conversion yields in this report have been derived from 2 main sources [99, 100]. Further, several values were pulled from multiple literature sources and averages were determined for each feedstock and fuel. A summary of the process yields are presented in table **??**.

It is important to note that the majority of these values are conversion rates achieved during experimental trials, which many times, differ from the theoretical yield values. For example, the study by Davidsson, Gruvberger et al. tested methane yields for source-sorted organic fractions of municipal solid waste and found that the potential yields were almost always lower than the theoretical value by a factor of up to 30% [102]. To reflect a deeper, more realistic potential of the fuels, experimental values are used when available. The conversion values were usually expressed in $Nm^3/kgVS$ or m^3/ton and were converted to their respective energy counterparts. To keep homogeneity throughout all of the different sources and unit conversions, LHVs, densities,. The values chosen were the averages or medians of the value range.

Feedstock	**Ethanol**		**Methanol**		**Methane**	
Agricultural Residues	0.30	[101]	0.47	[99]	0.525	[100]
Forestry Residues	0.343	[102]	0.373	[103]	0.315	[100]
Livestock Manure	-		0.63	[99]	0.43	[104]
Biowaste MSW	0.234	[105]	0.23	[99]	0.273	[106]
Sewage	-		0.22	[99]	0.43	[100]

Table 7.1: Fuel yields per type of dry feedstock [MJ/MJ]

Fuel	**Volumetric LHV** (MJ/m^3)	**LHV** (MJ/kg)	**Density** (kg/m^3)
LNG (Methane)	36.46	55.5	0.657
LNG (Liquid)	23865	55.5	430
Ethanol	21315.15	27	789.45
Methanol	17740.8	22.4	792
Feedstock			
Agricultural Residues	740	18,5	40
Forestry Residues	4806	18	267
Livstock Manure	6000	15	400
Biowaste MSW	6000	15	400
Sewage	6720	12	560

8

Verification & Validation

The mathematical model and supply/demand scenarios created in the preceding chapters are approximate imitations of a real-world system. The results obtained are subject to many physical limitations, assumptions and constraints. Therefore, the model's inputs and outputs should be tested, verified and validated.

The focus of this chapter is the model itself. To test whether the model runs correctly and completes its intended function, a series of tests, sensitivity analyses and data comparisons will be done.

Starting with verification, the model will be run for a base case and the outputs will be subject to a sensibility analysis. Then a detailed analysis of the model will be presented and interpreted. Lastly, the results will be validated next to current models and actual figures.

8.1. Model Verification

In the context of this study and model, verification refers to the extent to which the model/solution method performs in accordance with the initial modelling mathematics and assumptions. To do this, several checks will be employed, namely:

- A double-check of the mathematics and coding of the model to make sure there is consistency between the formulation and the algorithm.
- Check whether the solution provided by the solver is sound and logical (e.g. doesn't violate any constraint, rules or laws).
- Feed deliberately designed feasible and infeasible solution inputs into the model and test whether it can confirm the feasibility/infeasibility of the provided solution.
- Change input data to see if the model/algorithm behavior changes. This can be best done through a sensitivity analysis.

With regards to the first point, all values from equations and input parameters are checked to ensure the right units are used. All material flows and energy terms are expressed in GJ. All costs are expressed in terms of euros, and where applicable, €/h or €/GJ. Further, all input parameters loaded from an external database (excel) to the program are checked on both the database and the model to make sure that both the values and respective indices match.

To check whether the solutions are sound and logical, all decision variables are checked to make sure they follow all the imposed constraints. That is, they should all pass the following tests:

- All results should be positive.
- There should be an energy balance between all biomass, intermediate product and fuel flows (taking into account all conversion efficiencies and fuel conversion yields).
- The total amount of each fuel produced should not surpass the total fuel-specific refining capacity of the model.

- The energy demand should be satiated at each port (or if it isn't, the deficit at that port and time period plus the amount shipped should equal the total demand).

Upon a thorough inspection under several supply/demand cases, all of these tests were found to hold. Lastly, the sensitivity analysis will be performed in the following section.

8.2. Sensitivity Analysis

The sensitivity analysis will be undertaken to more deeply understand the behavior of the model. By altering some of the key input parameters, changes in model outputs can be seen, assessed and reasoned. The changes should make sense and be consistent with the formulation. For all sensitivity analysis calculations, the same scenario will be used; the baseline supply scenario (low competition) and the medium demand case. There is no particular reason why this specific scenario is run (aside from the fact that it represents a middle-ground for all scenarios), but what matters is that the same conditions are run for all testing. Moreover, throughout the entire analysis, the same weights of 0.5 will be used for each objective function. For the environmental objective, similar to what was explained in Section 7.3, the cost of emissions will be equal to the assumed cost of emissions for each year.

The following graphs show the effect of altering parameter values on the resulting objective functions.

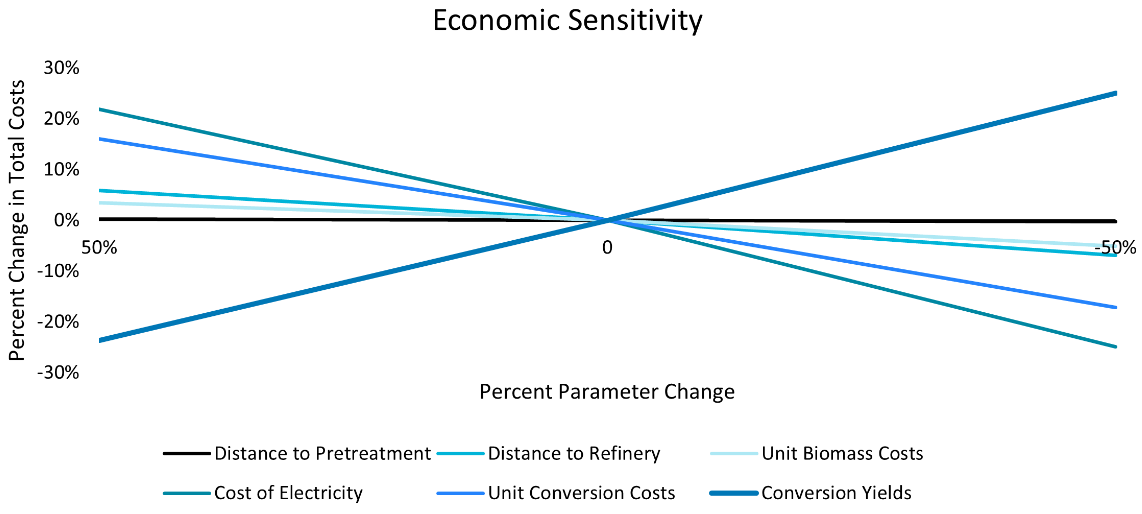


Figure 8.1: Economic sensitivity to altering key parameters.

To begin, the distances are altered for the first two transport legs (truck transport of biomass and intermediate). The transport legs associated with these two distances present the highest relative costs (cost per energy transported) in the entire transport chain as the specific energy content of the transported goods is lowest and due to the relative cost of transporting by truck (which is less economically efficient than shipping). This serves to assess the effects of altering the distances between the biomass collection site to pre-processing site and pre-processing site to refinery, which are uncertain parameters. The shipping route distances are not tested as there is no workaround the fixed geographic locations of ports. As can be seen in figures 8.1 and 8.2, positive changes in the distances are associated with positive cost and emission increases, though the costs show higher sensitivity. In specific, distance D^{SR} results in a cost change of +6% and -7% when altered to +50% and -50% of its respective value(s). Though not an enormous change, it would be interesting to further investigate the effects of this transport distance on the whole system.

The rest of the parameters also seem to give expected results when they're altered. Positive/negative changes in unit costs result in positive/negative (respectively) changes in total costs. Of particular notice is the electricity cost, which gives a similar change to altering the conversion cost. Regardless, each of these parameters have about 20% influence over the system costs. This means that the pretreatment and conversion costs will most likely make up the largest portion of the total cost. For the conversion yields, the trend is opposite to the other parameters; a positive change results in a cost reduction and a negative change results in a cost increase, as can be expected.

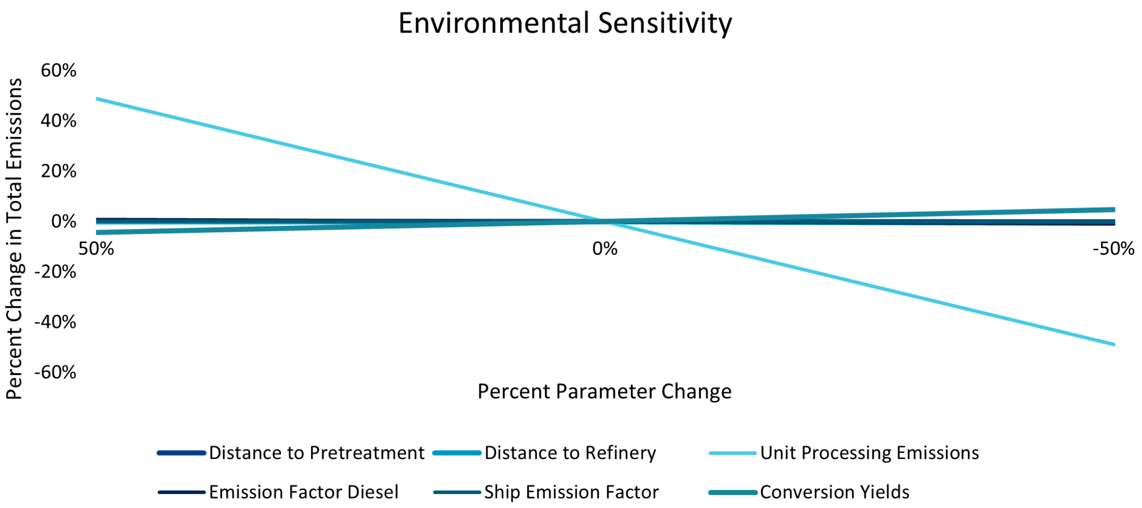


Figure 8.2: Environmental sensitivity to altering key parameters.

Similarly, an analysis is carried out for the emissions. At first glance, the environmental sensitivity is much less responsive than the economic. Changes in both distances (D^{OPre} and D^{SR}) have almost a negligent effect on the total system emissions. Likewise, the fuel emission factors of ships and trucks don't have a great influence over the entire system. The total emissions also dont show much change when the conversion yields are changed which seems quite strange, as it would be expected that with increased efficiency would come lower emissions. This, however, can be attributed to the fact that processing emissions in the model are calculated based on the amount of outputted product and not the conversion efficiency. With that in consideration, the slight change makes sense, as the same or similar amount of fuel product is being created. This could, however, be an additional feature to consider in future models.

Lastly, it can be seen that the unit processing emissions have nearly a one-to-one change ratio with the system emissions. This heavily hints that the majority of emissions are a result of the conversion and pre-treatment phases. From this and the economic sensitivity behavior, it can be said that in order to reduce emissions and/or costs throughout the supply chain, the highest reduction potential lies within the conversion process itself.

8.3. Objective Function Trade-off

So far, the analysis has assumed that by equating emissions to a monetary value, both costs and emissions are of equal relevance and should be minimized the same. However, what if this is not the case? Suppose that one of the two objectives had more importance/urgency than the other. This can be the case for several reasons, because though comparable, costs and emissions are essentially not the same. To see how this would affect the results, figure 8.3 illustrates the trade-off between the economic and environmental objectives. The chart shows how the total type of produced biofuel (over the entire time period) would change in accordance with alternative objective function weights.

The image displays an interesting behavior. The fuel was purposely shown in terms of energy content rather than relative production content to illustrate how the altering environmental/economic weights also affect the total quantity of fuel produced. Since the model has no real immutable constraint to meet the demand, in favorable situations (in terms of lowering costs and emissions), the model opts to produce less fuel than demanded, or none at all. The only incentive the model has to meet the demand is through the deficit penalty (see section 4.3.1) which is ingrained into the cost function. For every gigajoule that isn't delivered to a demand site, the model must account for it by "spending money" on another fuel to replace that energy. By looking at the figure we see how this formulation has affected the results. Starting from the left side of the image, at an environmental weight of 1 and an economic weight of 0, the model has no incentive to produce any fuel and thus opts for the trivial solution. As the environmental weight is reduced and the economic weight is increased (left to right on the chart), the penalty for missing out on fuel demand becomes heavier and more serious. At an economic weight of 0.2, the model starts producing a small quantity of fuel because it becomes cheaper to produce that small amount (and pay the remaining deficit) than paying the 30 $€/GJ$ penalty for the entire

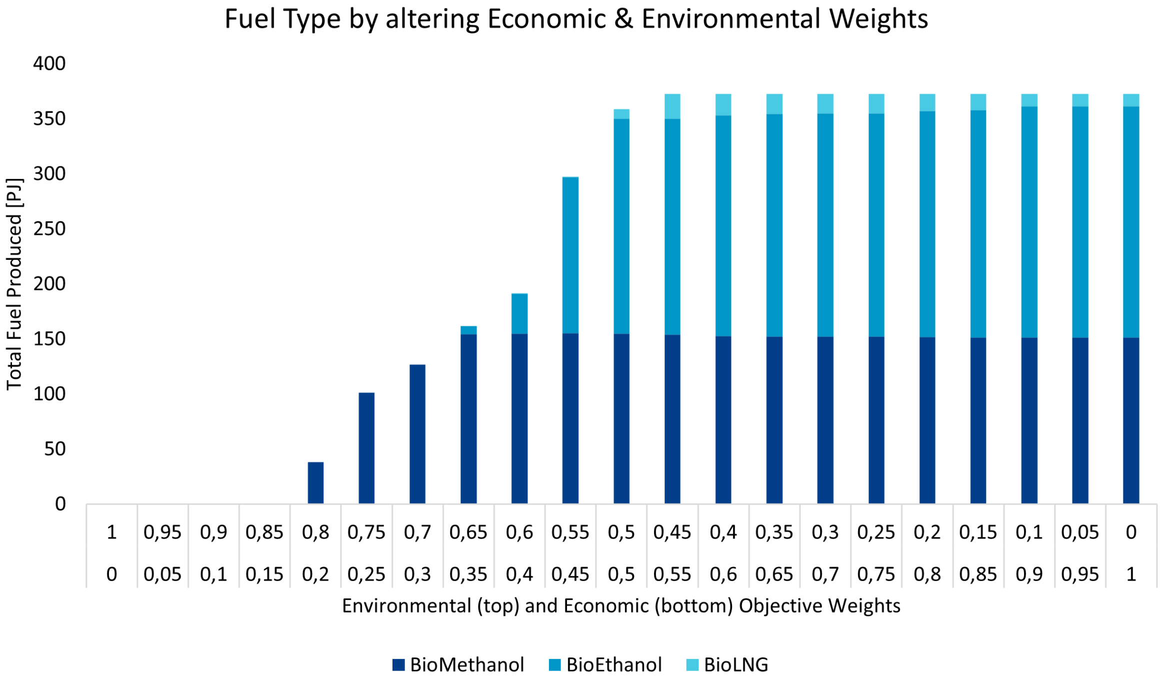


Figure 8.3: Caption

fuel demand amount. However, in this case, the model produces the cheapest fuel available. What is more interesting however, is the order and final amount of each type of fuel produced. As the economic objective becomes more important (moving left to right on the chart), the model first produces bio-methanol until a certain capped amount, then it does the same with bio-ethanol. This might suggest that methanol may be the cheapest fuel to produce in the model, followed by ethanol and lastly LNG. The cap of produced product may be a result of local refining capacity for the ran scenario. Another visualization of figure 8.3 is given in figure 8.4 which displays the type of fuel produced as a fraction of total produced fuel.

To see whether the aforementioned hypothesis holds any truth, the analysis will be performed again without refinery capacity constraints.

As can be seen above, without the capacity requirements, the model only produces bio-methanol at varying quantities depending on the environmental and economic weights. However, it can't be said with certainty that this is the cheapest fuel yet. This might be the case under the present supply and demand cases. Further analysis and scenario testing is needed to reach any conclusions with respect to costs. Further, to see how the deficit allowance has affected the fuel selection, the same trade-off will be performed again, but this time without allowing a deficit. This is shown in figure 8.6.

Without the deficit allowance, the trade-off graph takes a different shape on the left side, but ultimately reaches the same fuel proportions on the right side (as in figure 8.3). Essentially, what this graph says is that to reduce the environmental objective, a 0.5-0.2-0.3 ratio of methanol to ethanol to LNG is most favorable. With increasing economic weight, methanol reaches an optimal percentage of about 45 % production, ethanol 55% and LNG is reduced to 3% of production.

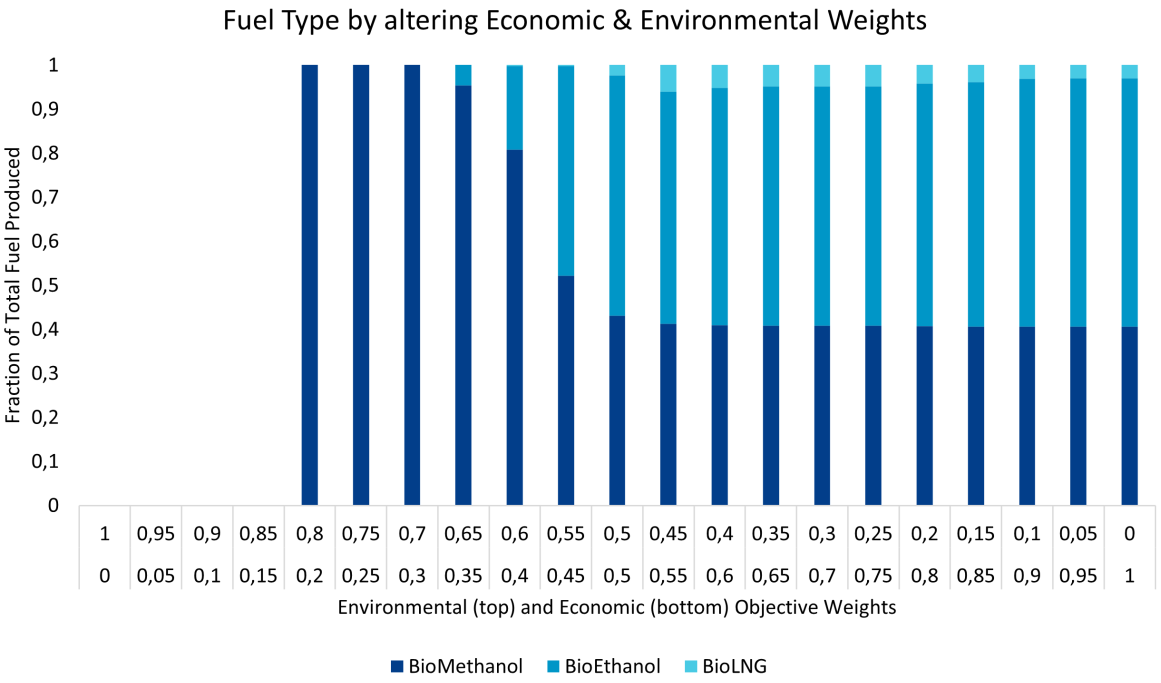


Figure 8.4: Caption

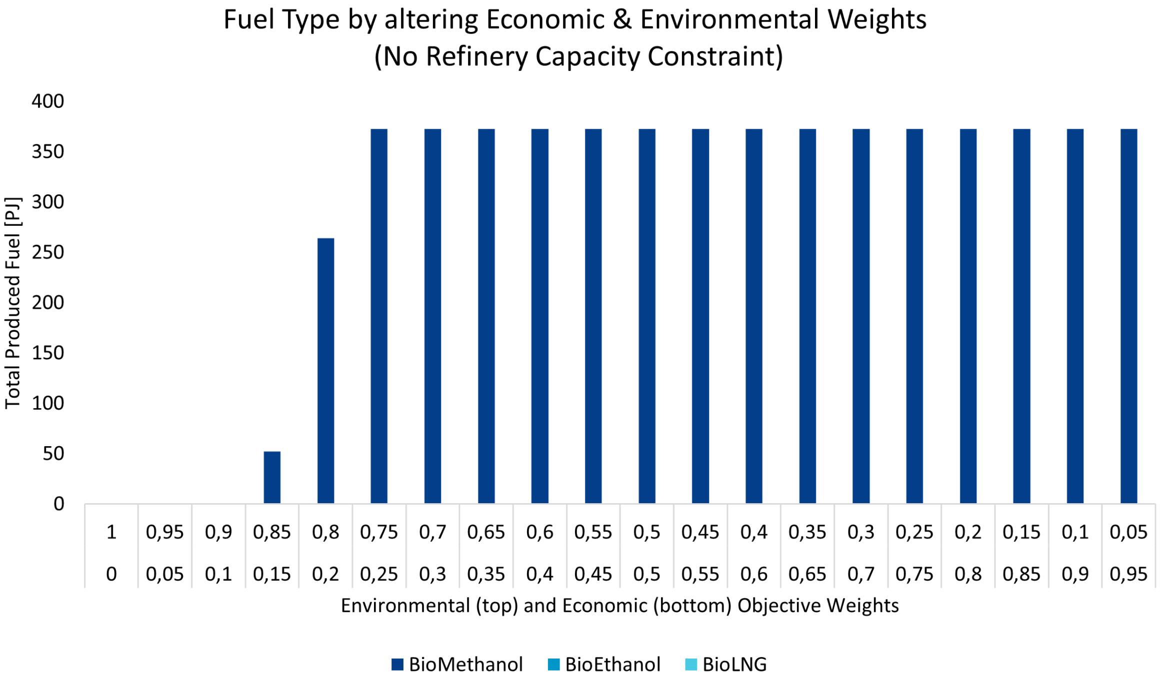


Figure 8.5: Caption

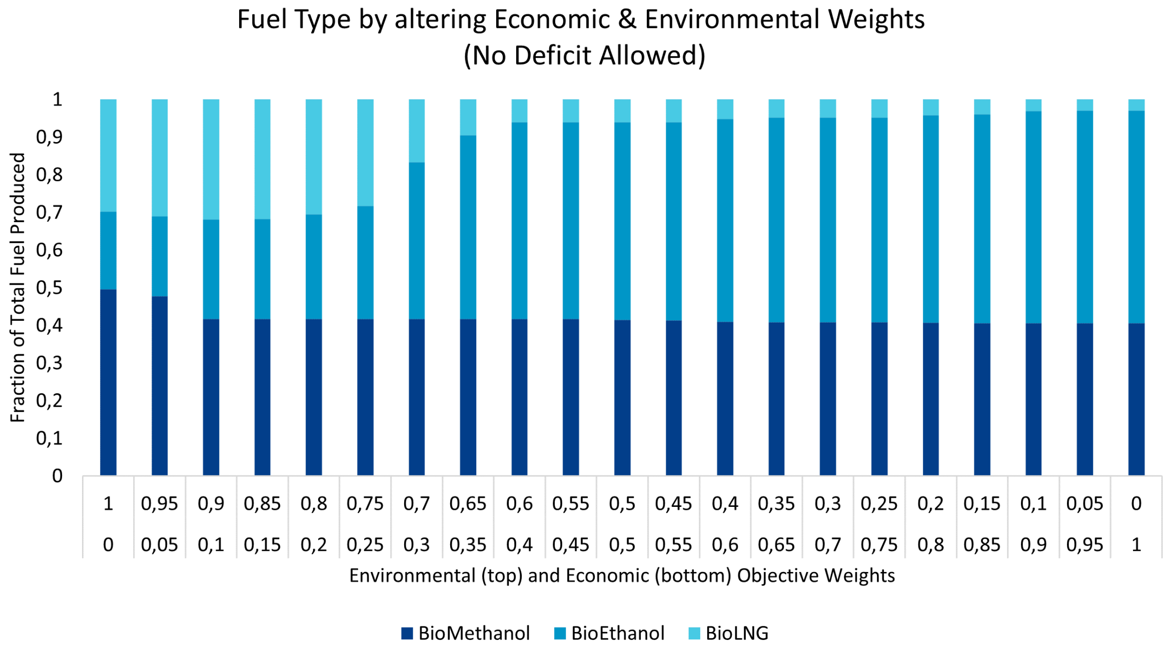


Figure 8.6: Objective trade-off without allowing a demand deficit.

8.4. Base Case Analysis

The next step in the verification process is an in-depth model analysis. Outputs will be pulled from the model and visualized to ensure all results make sense and are in accordance with the model constraints and ranges.

In this scenario, again medium demand and supply conditions are used. Since the demand is far below the supply and the model has no issues meeting the demand (in terms of other constraints), no deficit will be allowed.

In the context of this section, and for the rest of the analyses, total refers to the entire system, spanned over the six-years, unless otherwise stated.

8.4.1. Costs & Emissions

The first and arguably most important metrics of the system are the total costs and emissions. Assessing these values and the relation between the two are some of the main objectives of this report. To start, the total system costs are displayed in figure 8.7.

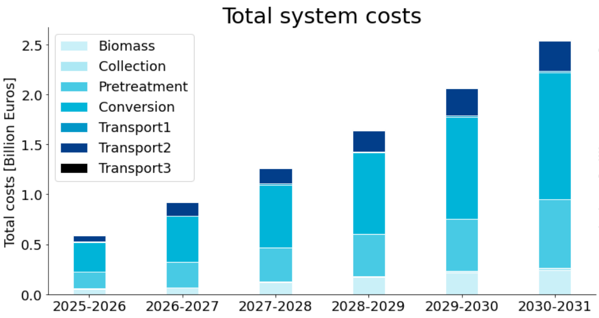


Figure 8.7: Total cost distribution for the base case in billion Euros.

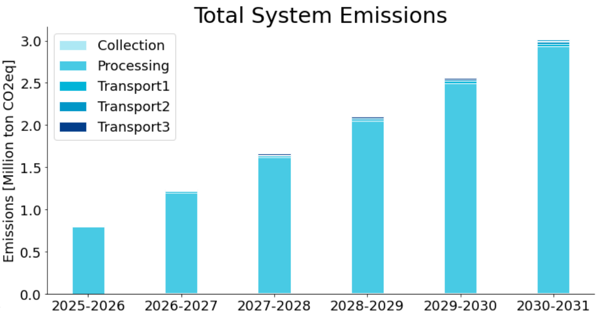


Figure 8.8: Total emissions distribution for the base case in million ton CO_2eq.

Not surprisingly, the total yearly costs increase linearly over time in a similar proportion to the demand. Since all equations are linear, the relationship between total cost and demand logically follows this trend, the same goes for the emissions. Though the relative fractions of each cost are not constant over time, the difference is small enough to not consider it. In terms of the total cost distribution, unsurprisingly, the majority of the costs are associated with the biomass conversion phase. In conjunction with the pretreatment process, the entire processing of biomass to fuel accounts for almost 78% of the total expenditure. Further, biomass and collection costs accounted for about 9% and 0.6% of the total costs, respectively. Transportation made up 12%, of which the vast majority (94%) was comprised of transportation of pre-treated biomass from pre-treatment site to refinery. The transport of raw biomass only made up about 5% of the transport costs, and the shipment of final fuel products was almost negligible at 1% of transport costs or 0.07% of system costs.

A similar distribution is seen in the emissions as with the costs, but more exaggerated. The emissions are dominated by the processing of biomass to fuel, which constitutes 96% of the total costs. The collection comprises 0.24% of the total emissions and the transport 3%. Unlike the distribution of transport costs, the division of the transport emissions follows a 0.3-0.5-0.2 split for the first, second and third transport legs, respectively. As can be seen, the distribution of transportation emissions is more equally divided than the costs.

In total, the system resulted in a fuel production of 0.37 EJ, 11.45 million tons of generated CO_2eq emissions, a cost of 9 billion euros with an average fuel cost of 24.22 €/GJ with approximately 30 kgCO_2eq/GJ. Chart 8.9 shows how the price relates to commonly utilized bunker fuels.

As was demonstrated in section 8.3, by altering the economic and environmental weights, different decision variables are obtained resulting in different fuel productions, and hence the total costs and total emissions change as well. Analysing how the costs vary as different total emission levels are obtained gives the marginal cost of emissions. That is, the Euro cost of lowering/raising emissions by one ton of CO_2. However, for better readability, it will be expressed here as the percent reduction of supply chain emissions per GJ of product compared to the fossil fuel comparator, as a function of costs. The fossil fuel comparator is an emission standard to which a comparison is made. The RED II outlines "for biofuels, for the purposes of the calculation referred to in point 3, the fossil fuel comparator EF(t) shall be 94 gCO_2eq/MJ" [42], which is a value slightly above HFO's.

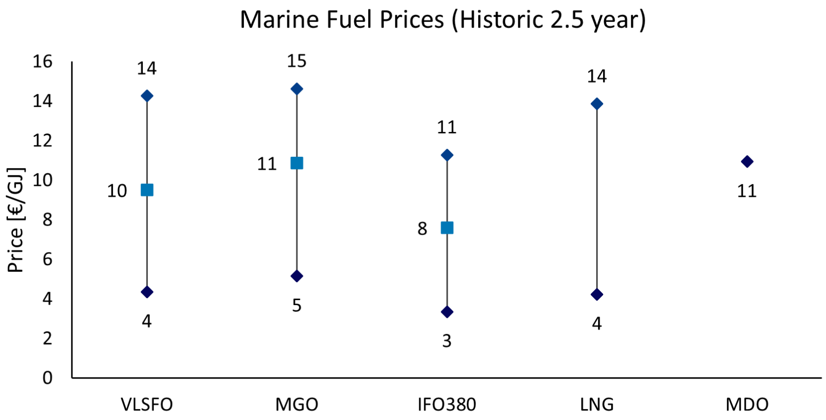


Figure 8.9: Historic Global 20 Ports bunker prices (average and range) from [?] (**IFO380 & IFO180** are Max 3.5% Sulfur Bunkers, **VLSFO** is Max 0.5% Sulfur fuel (Also known as IMO2020 grade bunkers), **MDO** is Max 1.50% Sulfur Distillate, **MGO** is, unless otherwise specified, a Max 1.50% Sulfur)

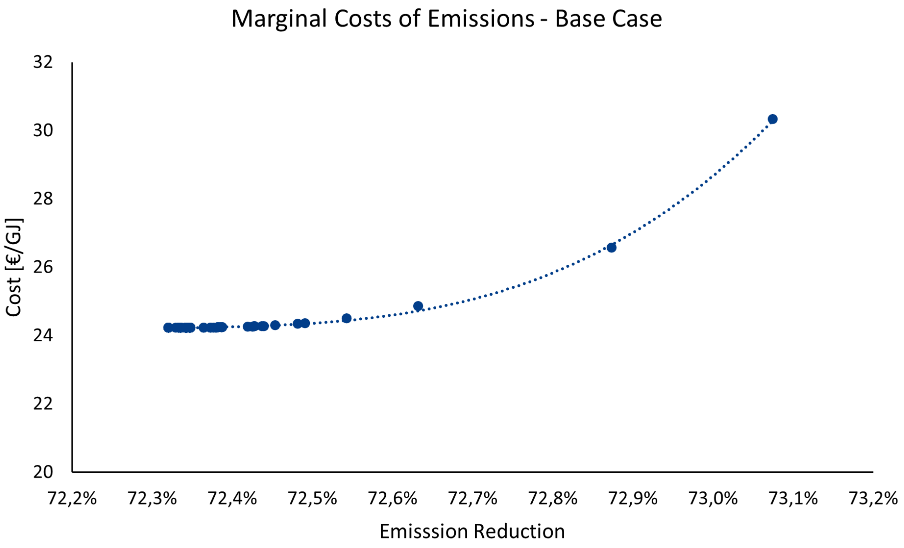


Figure 8.10: Marginal costs of emissions Base Case.

The figure shows the cost of reducing the emissions by a certain percentage of the fossil fuel comparator. As can be seen, the range of possible reduction is not broad, only a 1% change in emissions is achievable through cost alteration. This is due to the fact that the solution converges quickly and the objective function value remains relatively stable for different economic and environmental weights. The average emission reduction stands around 72.4%, though it can be reduced by a further 1%. Achieving this small reduction entails a large, disproportionate cost increase, which makes any higher reductions unappealing. However, the average emission reduction is quite considerable taking into account the relative price. Doubling the costs of the fuel reduces the emissions by more than half.

8.4.2. Product Flows

The following charts show the geographical flows for the intermediate products and fuels. The first graph (Figure 8.11) displays the movement of intermediate product from the countries to the refineries and the second describes the fuel flows from refineries to ports. Figures 8.14, 8.13 and 8.15 show the fuel-specific shipment from refinery to port. It is important to note that for these three graphs, the fuel flows have been rounded to the nearest PJ which means that any flow less than 0.5 TJ is automatically rounded down. Consequently, smaller, less significant flows between ports are not highlighted. Furthermore, due to the short time-frame of the problem, the flows only marginally change from year to year, therefore, the flows are visualized over the entire period.

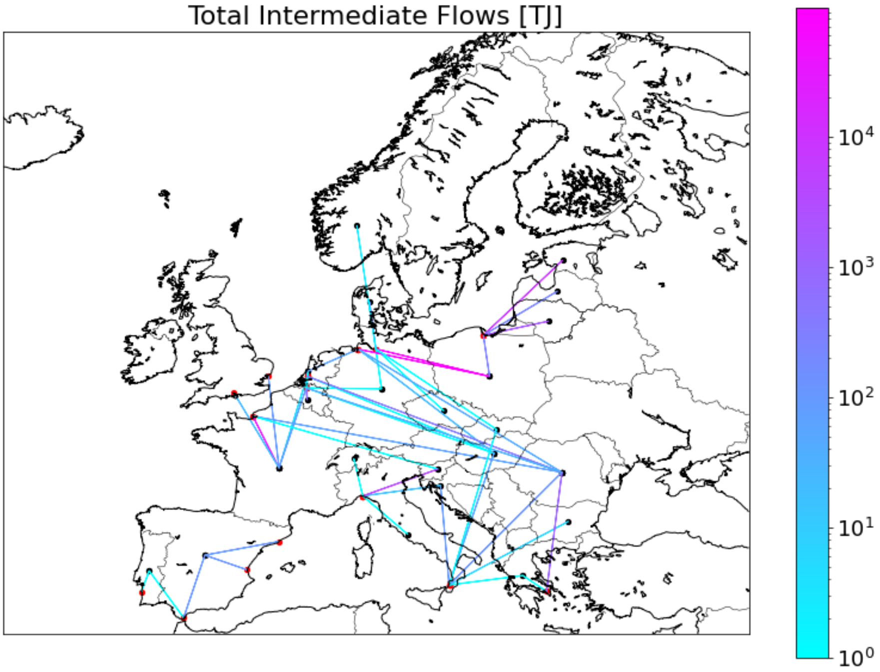


Figure 8.11: Total flows of intermediate products in TJ (base case).

In this scenario, biomass is sourced from 22 of the 27 countries, however, the majority is produced in Poland in the form of forestry residues, as shown in Figure 8.11. Almost half of all biomass (38%) is collected in Poland.

Under this demand framework, all refineries are utilized for conversion, though the refineries with the largest fuel productions in decreasing order are: Hamburg, Bremmerhaven, Gdansk, Le Havre, and Rotterdam. Due to the assumptions regarding biorefining capacity, Germany holds a clear advantage (in terms of refining capacity), and with the strategic location of the German ports (central Europe), its easy to understand why so much biomass is transported and converted there. The biomass flow to Le Havre and Gdansk is most probably a result of the high biomass use within those two countries, going to the nearest large port.

The main fuel exporters (from refineries) are Hamburg, Bremmerhaven, Gdansk and Le Havre, and the exports are usually within the local vicinity (northern European ports), except in the case of Algeciras, to which a large quantity of LNG and Ethanol are shipped to.

It seems that it is preferred to bring biomass directly to the demand site through inland routes and convert it at its final location when supply is available nearby. However, as is the case with Algeciras, when the demand is large, it becomes cheaper to ship the final product than to transport the raw material through inland routes. What is also interesting is the flow of the individual fuels. The production of bio-ethanol is centered around the northern sea ports and Le Havre, while LNG production is dominated by Hamburg and Le Havre. On the other hand, the production of bio-methanol is more distributed and more localized. Less shipment is needed from port to port.

8.4.3. Biomass Selection and Fuel Production

The type of biomass selected and the respective fuel produced from it is shown in graphs 8.16 and 8.17.

It is clear that the preferred feedstock are forestry residues followed by biowastes (to a much smaller extent). The reasoning for this is rooted in two main rationals. Firstly, as was seen in the analysis of costs and emissions, in both the economic and environmental sense, pre-treatment and conversion/processing methods make up the majority of the "system costs". The pre-treatment costs were defined in section 7.1.3 to be a function of the specific energy costs of drying and milling for each biomass type, which themselves are a function of the moisture content of the selected feedstock. Therefore, feedstock with lower moisture content are preferred over wet feedstock for cheaper processing. Additionally, lower MC feedstock are also cheaper to transport in the first leg of transport. Secondly, forestry residues are the most abundant resource throughout Europe. Though not

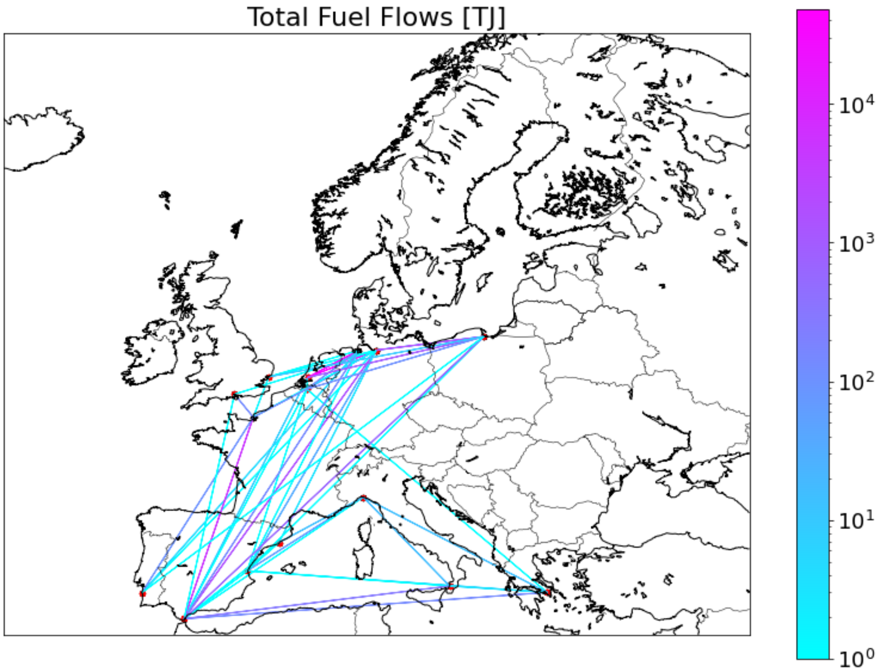
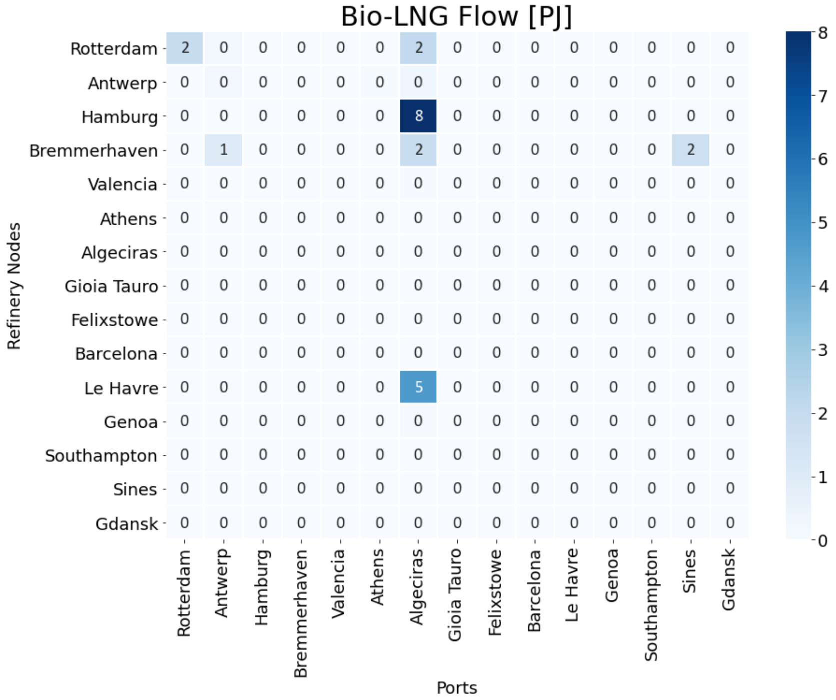


Figure 8.12: Total fuel flows in TJ (base case).

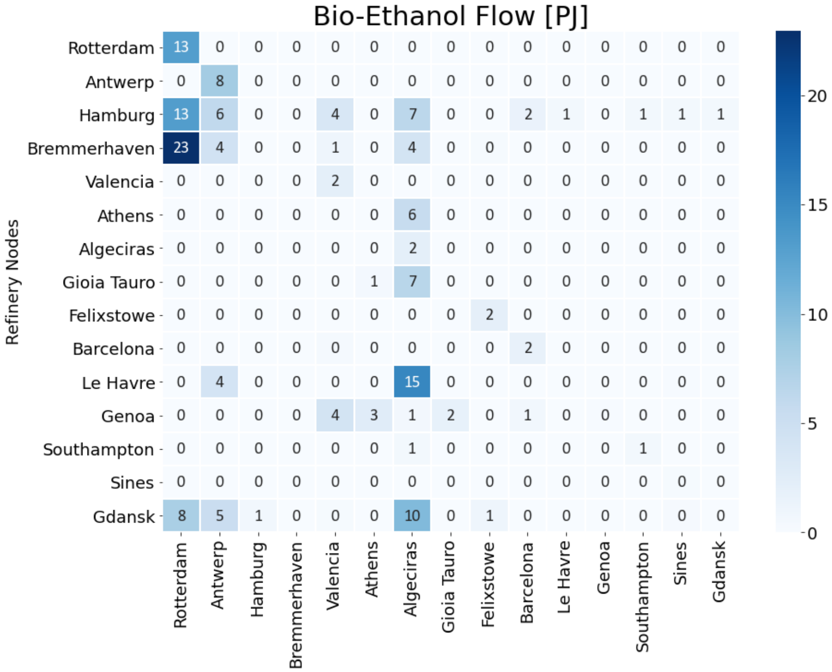


	Rotterdam	Antwerp	Hamburg	Bremmerhaven	Valencia	Athens	Algeciras	Gioia Tauro	Felixstowe	Barcelona	Le Havre	Genoa	Southampton	Sines	Gdansk
Rotterdam	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0
Antwerp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hamburg	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0
Bremmerhaven	0	1	0	0	0	0	2	0	0	0	0	0	0	2	0
Valencia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Athens	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Algeciras	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gioia Tauro	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Felixstowe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Barcelona	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Le Havre	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0
Genoa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Southampton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sines	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gdansk	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 8.13: Heatmap of total bio-LNG flows from refineries to ports for the base case [PJ].

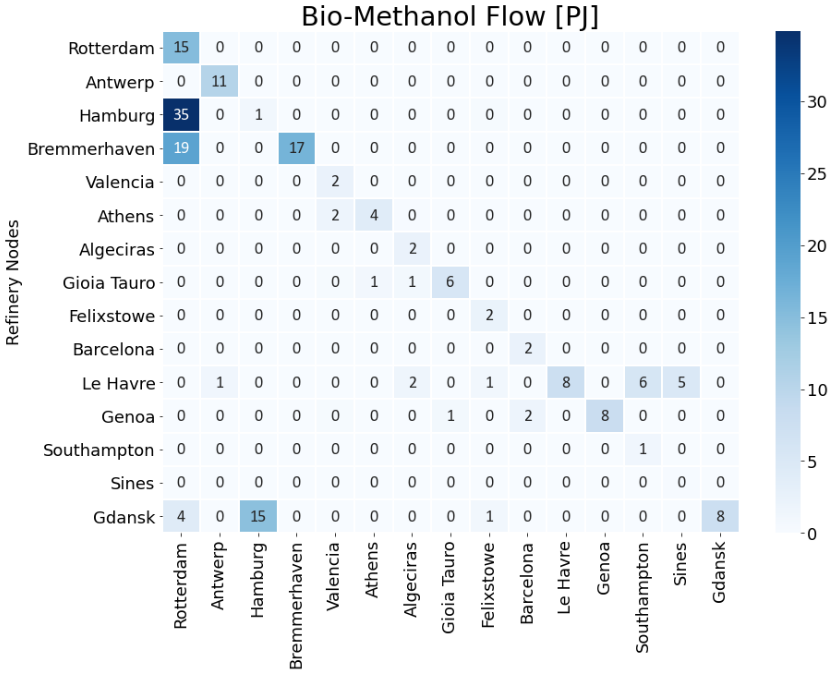
the cheapest (as both sewage and manure are considered to be free), the suitability of forestry for conversion into all three fuels makes it a good feedstock candidate. Biowastes, though characterized by a higher moisture content compared to forestry and agricultural residues, compensate for it through their high conversion yields and free purchase price.

It becomes easier to see now why the quantity of produced products are first methanol and then ethanol followed by LNG. In the case of 0.5-0.5 objective function weights, the environmental and economic objectives



	Rotterdam	Antwerp	Hamburg	Bremmerhaven	Valencia	Athens	Algeciras	Gioia Tauro	Felixstowe	Barcelona	Le Havre	Genoa	Southampton	Sines	Gdansk
Rotterdam	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Antwerp	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0
Hamburg	13	6	0	0	4	0	7	0	0	2	1	0	1	1	1
Bremmerhaven	23	4	0	0	1	0	4	0	0	0	0	0	0	0	0
Valencia	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Athens	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0
Algeciras	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
Gioia Tauro	0	0	0	0	0	1	7	0	0	0	0	0	0	0	0
Felixstowe	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
Barcelona	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
Le Havre	0	4	0	0	0	0	15	0	0	0	0	0	0	0	0
Genoa	0	0	0	0	4	3	1	2	0	1	0	0	0	0	0
Southampton	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
Sines	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gdansk	8	5	1	0	0	0	10	0	1	0	0	0	0	0	0

Figure 8.14: Heatmap of total bio-ethanol flows from refineries to ports for the base case [PJ].



	Rotterdam	Antwerp	Hamburg	Bremmerhaven	Valencia	Athens	Algeciras	Gioia Tauro	Felixstowe	Barcelona	Le Havre	Genoa	Southampton	Sines	Gdansk
Rotterdam	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Antwerp	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0
Hamburg	35	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Bremmerhaven	19	0	0	17	0	0	0	0	0	0	0	0	0	0	0
Valencia	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Athens	0	0	0	0	2	4	0	0	0	0	0	0	0	0	0
Algeciras	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
Gioia Tauro	0	0	0	0	0	1	1	6	0	0	0	0	0	0	0
Felixstowe	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
Barcelona	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
Le Havre	0	1	0	0	0	0	2	0	1	0	8	0	6	5	0
Genoa	0	0	0	0	0	0	0	1	0	2	0	8	0	0	0
Southampton	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Sines	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gdansk	4	0	15	0	0	0	0	0	1	0	0	0	0	0	8

Figure 8.15: Heatmap of total bio-methanol flows from refineries to ports for the base case [PJ].

hold equal importance. The costs and emissions are dominated by the whole conversion process, and the costs of conversion ranked in increasing order follows the order: ethanol, methanol, and LNG. The unit processing emissions are lowest for ethanol and highest for methanol. However, on average, the conversion yields for bio-LNG are somewhat higher than for the other two fuels from the selected feedstock. In the economic and environmental sense, ethanol would seem to be the best option from a basic perspective. Further, the total capacities of refineries for ethanol and methanol are much larger than LNG's and are also distributed more

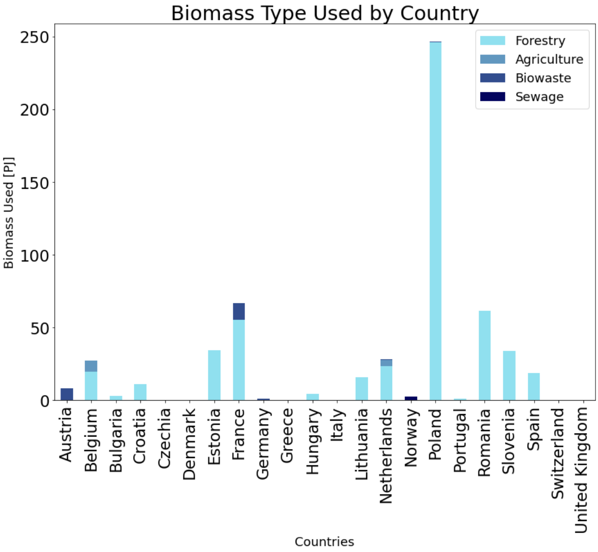


Figure 8.16: Biomass type used per country for base case [PJ].

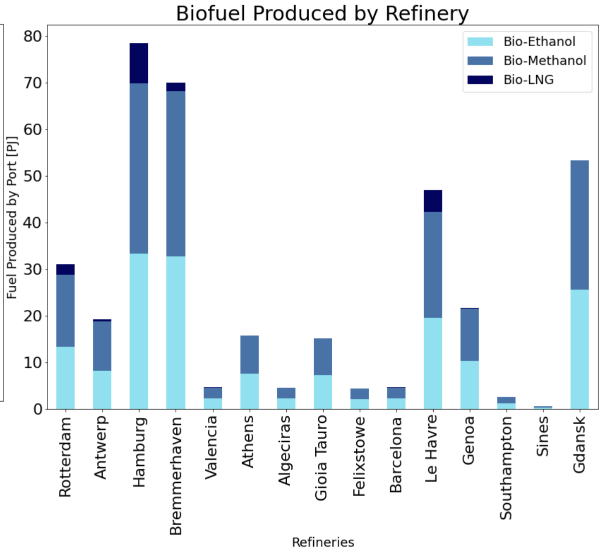


Figure 8.17: Fuel type produced by port for base case [PJ].

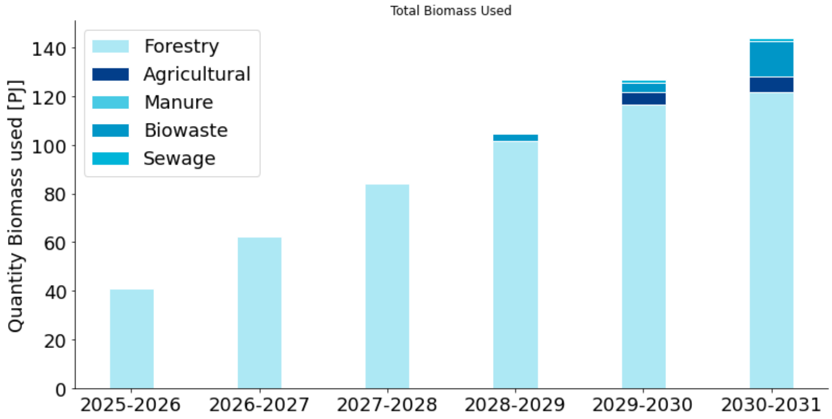


Figure 8.18: Caption

evenly throughout Europe. This is why in the first years, as figure 8.18 shows, the system only uses forestry residues and eventually turns to other feedstocks as the demand increases and capacity limitations start arising.

8.5. Validation

With the software running and having retrieving the desired outputs, the next step is to validate the results to assess whether they are accurate and within realistic bounds. Few studies have explored the production of biofuels in the EU, and far less have have done so for the outlined fuels using second generation biomass. As expressed earlier, the majority of papers within this theme have been done on a national or regional scale. However, of the ones within a similar framework, a certain comparison can be made while taking into account the fundamental differences.

The main outputs that can be compared are the costs, emissions and biomass use, as these are the most significant outputs of this model.

To start, the fuel prices are compared to literature to gauge the range they find themselves in. However, in this report only costs will be looked at, as the other two outputs vary significantly on the technologies and feedstocks available.

In terms of the cost distribution, Moreti, Milani et. al developed a detailed MILP formulation for the optimal design of advanced biofuel supply chains and tested their model on an Italian case study for the production of methanol. The average price of the final product ranged from 418.7-433.4 €/T (21-22 €/GJ). Further, a review by the IEA established a series of cost ranges based on several studies for bio-methanol, bio-ethanol and bio-methane. From table ??, it can be seen that the costs from this study are slightly higher than the compiled results, but still fall within reasonable range.

Biofuel Type	Production cost range [EUR/MWh]	Production cost range [EUR/GJ]
Biomethane from Biogas	40-120	11-34
Cellulosic Ethanol	85-103	24-29
Biomethane& Ethanol from waste	67-87	19-24
Biomethane & Biomethanol from wood	60-80	17-23

Table 8.1: Range of biofuel prices compiled from several similar studies [14].

9

Scenario Analysis

The following chapter explores the results of the model under a set of scenarios that are meant to test various future possibilities and conditions. The scenarios will first be explained and presented. In the last section of the chapter, a side-by-side analysis is done to compare all scenarios and draw any fundamental conclusions.

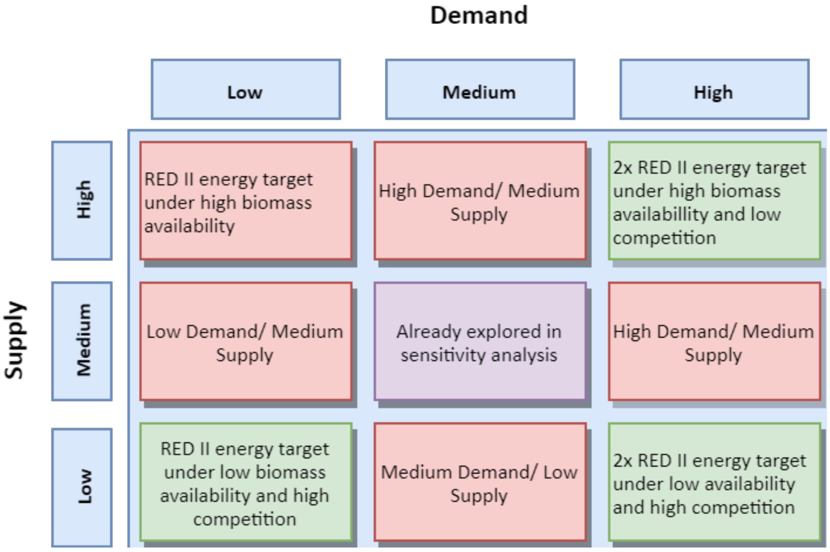
9.1. Scenario Overview

Each of the ensuing scenarios serves a utility in answering the main research question and subquestions. To understand why each of the selected scenarios are run under the given conditions and what usefulness they will serve in the analysis, a brief overview of each scenario is presented in the list below.

The first three scenarios relate solely to the supply and demand framework presented in chapters 5 and 6. Of these, only the extremes will be tested, as not every case is needed to draw conclusions. The table below highlights which scenarios will be analyzed from the supply and demand situations. The succeeding scenarios consist in altering certain fundamental conditions that have been assumed for the model.

Similar to what was done for the base case, a supply deficit will not be allowed for models in which the supply exceeds demand and are feasible. In cases where it doesn't, a deficit will be allowed and expressed in terms of energy per port.

It is important to also note that while several scenarios are presented, they do not all hold the same level of veracity (in terms of probability of occurrence) or importance. Some scenarios are solely run and presented to provide insight and deeper understanding into the model and the research questions. To do this, sometimes it is useful to present unrealistic/improbable scenarios.



Supply \ Demand	Low	Medium	High
High	RED II energy target under high biomass availability	High Demand/ Medium Supply	2x RED II energy target under high biomass availabillity and low competition
Medium	Low Demand/ Medium Supply	Already explored in sensitivity analysis	High Demand/ Medium Supply
Low	RED II energy target under low biomass availability and high competition	Medium Demand/ Low Supply	2x RED II energy target under low availability and high competition

Figure 9.1: Overview of supply and demand situations, selections highlighted in green are covered in this chapter.

1. **High Demand Low Supply**
   The first scenario run is a high demand low supply case meant to account for the least favorable conditions. This combination will set an upper limit on the costs and emissions that can be expected.
2. **High Demand High Supply**
   This case will serve to show the model at its full load to see how product flows and systems outputs change.
3. **Low Demand Low Supply**
   A low demand low supply scenario sets the lower left boundary on figure 9.1. Will the model opt to create a large deficit or will it solve the system completely and fulfill the demand?
4. **Equal Demand In All Ports, Medium Supply**
   For each demand scenario, the proportion of demanded fuel for each port is constant and largely based on historic data. However, with biofuels, there is still uncertainty with regards to port-specific demand. Setting the energy demand at all ports equal to each other can give a broader sense of the preferred trade routes along Europe under alternate circumstances. Further, it can answer the question of whether inland routes are more preferable than sea trade under certain conditions.
5. **No Refining Capacities Constraint, Medium/Equal Demand Medium Supply**
   As will be demonstrated in various of the scenarios, when the demand exceeds a certain amount, the limiting factor in supplying the fuel becomes the capacities of the bio-refineries. This constraint forces the system to act in a way that is predetermined and bound by the established physical capabilities of each country. Therefore, the full insight into the geographical aspect of the problem is not fully exploited. For this reason, a scenario will be run in which the refining capacity constrain is discarded. This in turn will allow for a better understanding of system flows.
6. **Running the Model for Each Fuel at a Time**
   Three scenarios can be derived from this one; one for each fuel. In each case, only one specific fuel is allowed to be made. It could be interesting to see how the model behaves solely for each fuel.

9.2. Scenario 1 - High Demand Low Supply

This first scenario is based on the worst-case conditions for the model. A high biofuel demand in combination with a low biomass availability, along with the other constraints, creates a setting in which the model reaches one of its upper bound limits. For this case, the total energy demand in the six-year period is 1.4 EJ and while the total supply of biomass stands at a considerable 6.8 EJ, the bio-refineries have a total output capacity of about 1 EJ during the entire span. Therefore, for this case, the limiting constraint is the biorefinery capacity, and the deficit decision variable, DT, is needed to allow for a deficit at each port.

What is notable about this scenario is that despite the lack of capacity, when given the choice of creating a deficit at the cost of paying for the energy replacement, the system opts to create a larger deficit than what is actually needed. In other words, the model does not use all available refining resources, and instead pays for the cost of fuel replacement at 30 €/GJ. This is already an indication that the system costs and the marginal costs will be significantly higher than the medium supply/demand cases. What the system is doing is discarding any options that would cost more than 30 €/GJ to produce. So, to prevent the system from creating a much larger deficit than what is necessary, the penalty cost of the deficit is raised to 100 €/GJ. This way, the system is highly incentivized to create fuel but not also discards production lines that are too expensive and significantly increase the average production price. It is found that at higher penalty costs, the system significantly changes its overall behavior and the deficit becomes more important than optimizing production lines. This same deficit cost will be maintained for all scenarios in which the demand is larger than the supply (scenarios 1,2 and 6). The optimal intermediate and fuel flows are presented in figures 9.36 and 9.39. From these figures, it becomes immediately evident that there are some differences between these flows and the flows for the base case. To start, the intermediate product outflows from the countries are more dispersed and seemingly erratic. Instead of following the same nearby route to a refinery, the biomass travels to various refineries outside of the country's nearby vicinity. This is a result of the refining constraint. Now, when the capacities of nearby refineries are maxed out, the biomass has to travel further to reach a refinery with sufficient capacity.

With respect to the fuel exports, the dominant players in the north (Hamburg, Bremmerhaven, Gdansk and Rotterdam) remain, however, in the south, Athens and Gioia Tauro emerge as large export hubs for the surrounding area. Some of the most notable changes in the fuel flows include the following:

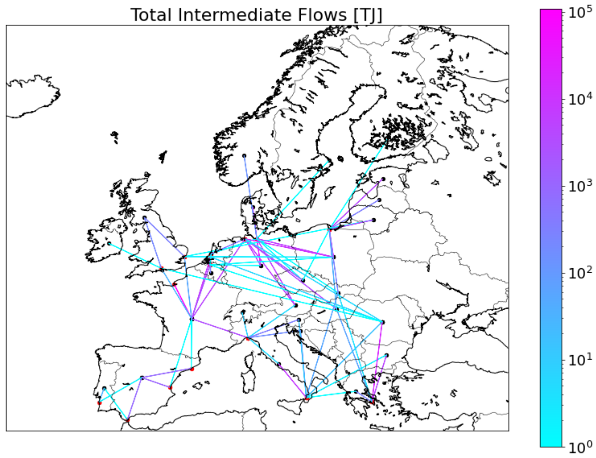

Total Intermediate Flows [TJ]

Figure 9.2: Map of total intermediate flows in Europe for Scenario 1 [TJ]

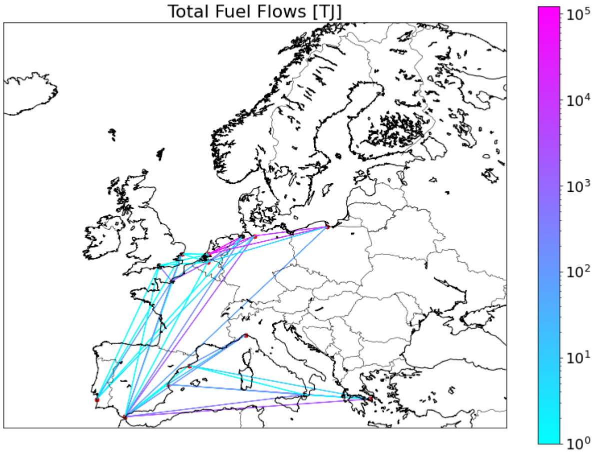

Total Fuel Flows [TJ]

Figure 9.3: Map of total fuel flows throughout Europe for scenario 1 [TJ]

- Antwerp no longer is a fuel exporter.
- Athens begins exporting to Gioia Tauro, Barcelona and Genoa, ontop of Algeciras and Valencia.
- Bremmerhaven, Felixstowe, and Gdansk begin exporting to Sines.
- Bremmerhaven stops exporting to Mediterranean ports, except Algeciras, to which it still ships a large amount of fuel.
- Gdansk discontinues transporting fuel to Valencia.
- Hamburg exports to four less ports (Valencia, Athens, Felixstowe, Barcelona) than previously.
- Rotterdam stops exporting to Algeciras, and now only exports to Antwerp.

It can be said that under these conditions, northern ports remain important for the shipment of fuels in northern Europe, however, as is seen in both biomass *and* fuel flows, certain southern ports (Gioia Tauro and Athens) become significant in the production and distribution of fuel across the south. In general, there is less seaborne distance being travelled than in the base case scenario and ports begin to group themselves by geographical locations. The three main areas identified are the northern sea, the English channel up to Sines, and the Mediterranean sea.

The capacity limitation is also reflected in the choice of biomass and production of biofuel. Both are shown in figures 9.11 and 9.12. As can be seen, there is still a strong proclivity for the system to use forestry residues, however, the increased supply combined with limitations on fuel production cause the system to also use less-than-desirable biomass options. As shown in figure 9.6, the system first uses forestry residues as much as possible, reaching the capacity limitation for that feedstock. At that point it becomes cheaper to source different biomass and convert it nearby than to transport forestry residues any further. In the first year, the majority of biomass used is forestry, followed by agriculture, biowaste and an even smaller amount of manure.

The energy deficit at each port and year is described in table 9.1. Not surprisingly, the major deficits are in the large ports such as Algeciras, Rotterdam and Antwerp but also in smaller ports like Valencia, Gioia Tauro and Sines. Algeciras, however, carries the heaviest weight (in terms of deficit). The main reason for this is the fact that though not lacking in biomass sources, the countries in the vicinity of Algeciras (Portugal and Spain) lack the infrastructure to locally produce the amount of demanded fuel at this site. Both Algeciras and Sines are ports which import their fuel supply from the northern economies, and since the trade routes are quite long (shipping distance from north sea), they are the first to be cut-out in the case of a shortage/constraint. Sines can mainly supply itself but also relies on shipments from the UK, France and Germany, which isn't possible when the demand substantially increases in the later years. Rotterdam is supplied mainly by both German ports, Gdansk and itself, however, in the later years, as with Antwerp, the local production capacities meet a cap and the deficit is created.

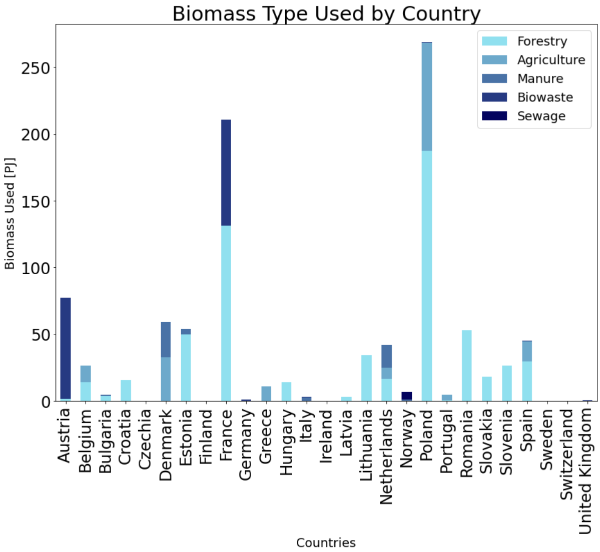


Figure 9.4: Total sewage sludge production in Europe (2020) in PJ

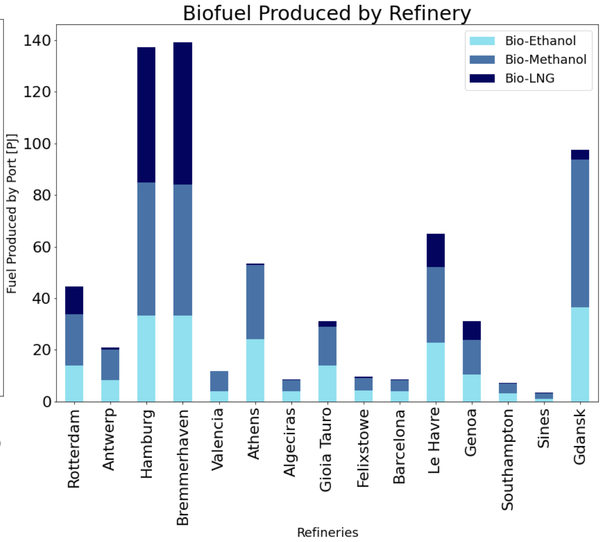


Figure 9.5: Technical sludge available for biofuel use (2020).

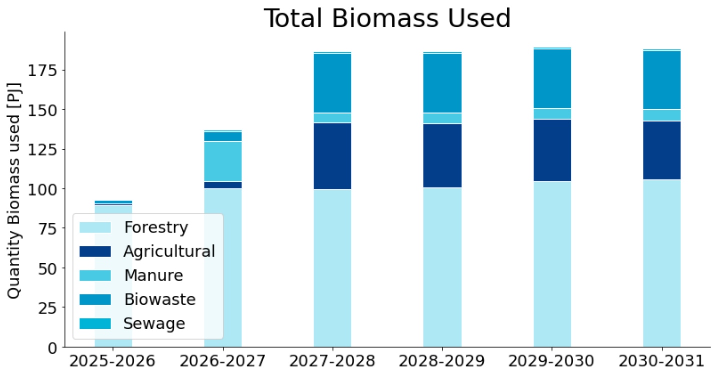


Figure 9.6: Total types of biomass utilized per year.

	2025-2026	**2026-2027**	**2027-2028**	**2028-2029**	**2029-2030**	**2030-2031**
Rotterdam	0	0	0	0	16.58	38.10
Antwerp	0	0	0	10.21	19.32	24.26
Hamburg	0	0	0	0	0	0
Bremmerhaven	0	0	0	0	0	0
Valencia	0	0	0	0	1.11	7.03
Athens	0	0	0	0	0	0
Algeciras	0	0	2.66	28.66	40.66	49.49
Gioia Tauro	0	0	0	0	0	0
Felixstowe	0	0	0	0	0	2.37
Barcelona	0	0	0	0	0	0
Le Havre	0	0	0	0	0	0
Genoa	0	0	0	0	0	0
Southampton	0	0	0	0	0	0
Sines	0	0	0	2.99	3.92	4.92
Gdansk	0	0	0	0	0	0

Table 9.1: Energy deficit for scenario 1 [EJ].

The costs and emissions tell a similar story. In the first three years, the costs and emissions increase linearly until the capacity constrain is met, afterwhich they plateau. The change in total biomass composition per year is reflected in the first two years where there is a significant uptake in the use of manure as biomass. This is manifested in a proportional decrease in biomass costs and an increase in inland transport costs.

Overall, the average price and emissions for the produced products equal 31.6 €/GJ and 29.2 gCO_2eq/GJ, respectively. This can also be observed from graphs 9.7 and 9.8 that there is a substantial increase in both costs and emissions. Also, the proportion of inland transport costs is substantially raised in the last four years (compared to base case) due to the new routes that have to be travelled.

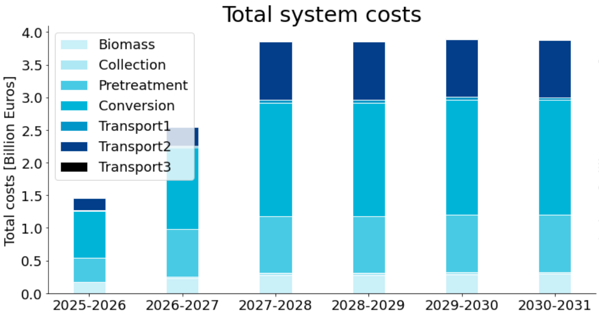


Figure 9.7: Distribution of costs per time-period in billion euros (Scenario 1).

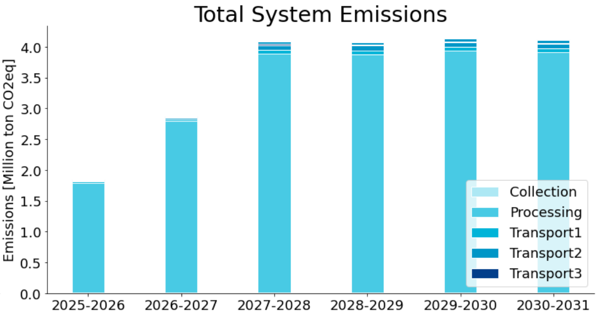


Figure 9.8: Distribution of emission per time-period in million ton CO_2eq (Scenario 1).

9.3. Scenario 2 - High Demand High Supply

The first scenario was useful in demonstrating which biomass types are most preferable under the given conditions and what the limiting factor is under high demand cases (refining output capacity). Under this second scheme, the demand remains high, but the supply is increased to the high condition. By doing so, it is possible to compare the biomass utilized as well as the costs and emissions to show just how much effect the biorefining capacity has.

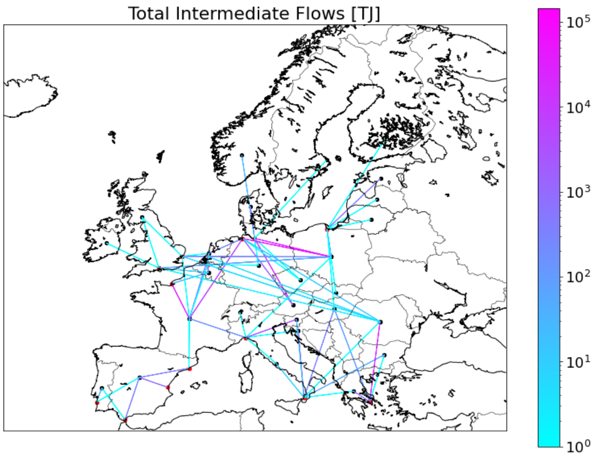


Figure 9.9: Map of total intermediate flows in Europe [TJ] (Scenario 2)

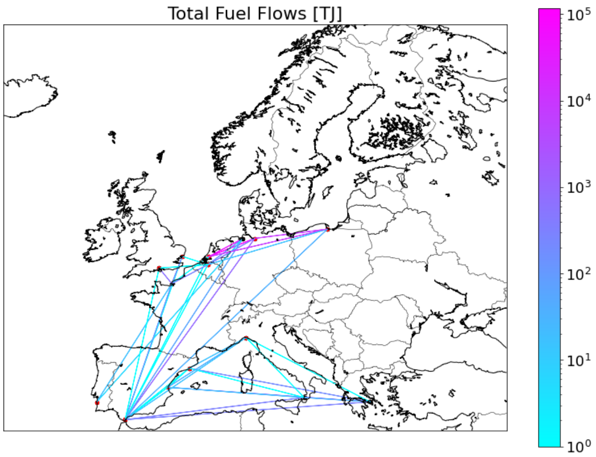


Figure 9.10: Map of total fuel flows throughout Europe [TJ] (Scenario 2).

Similarly to Scenario 1, the lack of biorefining capacity is the limiting factor which causes the appearance of new routes between countries and refineries. However, due to the increased supply of biomass, the total system emissions and costs are brought down, as now higher amounts of preferred biomass can be used. This system results in an average energy price of 29.5 €/GJ and emissions of 32 CO_2eq/GJ; a decrease in cost, but an increase in emissions. The decrease in cost is due to the higher availability of preferred biomass and the increase of emissions is due to different fuels being produced (due to refinery proximity from collection site). In terms of the cost and emissions distributions, they are quite similar to scenario 1. The main differences between these two cases are the amount of routes travelled, which in this case are slightly reduced due to a higher availability of biomass, specifically forestry residues, which have high conversion rates for all three fuels and high energy densities for efficient inland travel. However, the deficits occur in the same places and same years but at a smaller amount. What can be said about this, since the refining capacity remains the same, is that due to the increase of biomass, fuels with higher yields but also higher emissions are produced to come as close as possible to meeting the demand.

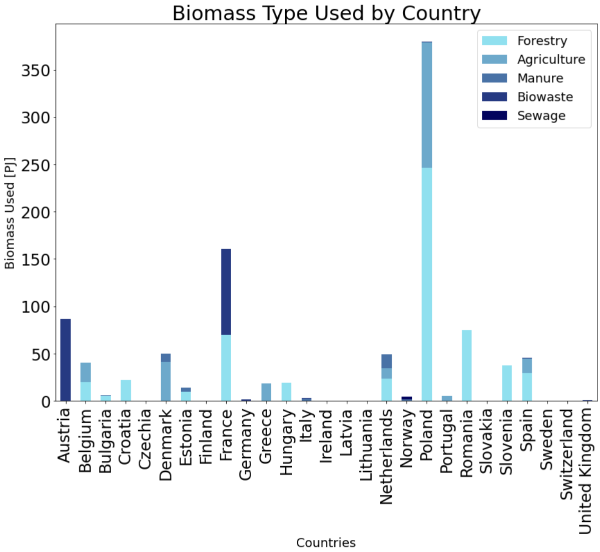


Figure 9.11: Total sewage sludge production in Europe (2020) in PJ

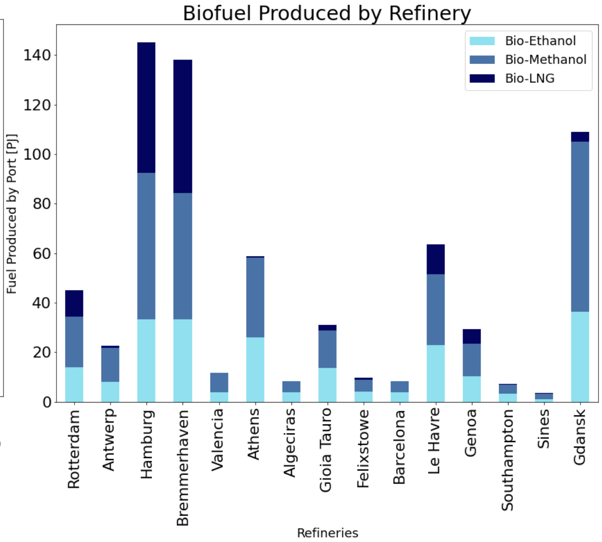


Figure 9.12: Technical sludge available for biofuel use (2020).

9.4. Scenario 3 - Low Demand Low Supply

The results of the low demand low supply scenario are very similar to those from the base case (medium demand, medium supply). The low energy demand stays relatively similar; only decreasing about 2% relative to the medium case. The biomass supply on the other hand, decreases on average by 14-26% (depending on the year) compared to the medium supply. Although a seemingly large value range, the supply of biomass in each country is still large enough for the results to remain relatively unchanged.

The main difference that is seen in the intermediate flows is that with the reduced demand, there is a slight reduction in transport paths. In other words, due to the decreased demand, a lower quantity of biomass can flow to the nearest optimal refinery before running into capacity constraints. This has the effect of lowering the proportionate amount of inland transport costs and increasing the fraction of shipping costs. This transformation shows that when allowed, the system prefers to first optimize the inland transport routes and then the shipping paths. Following this logic, the main differences in fuel flows is the increase in paths originating from refineries to ports. However, both of these effects are very small in scale.

The total costs and emissions of the system are 8.97 billion euros and 11.18 billion tons of CO_2eg, respectively. Considering the total amount of fuel created, this results in an average price of 24.65 €/GJ and specific emissions of 30.73 kg CO_2eq/GJ.

An interesting distinction between this case and the base scenario is the allocation and use of biomass. While Poland remains the main forestry and overall biomass supplier, France's supply picks up a notable amount while Poland's decreases. Also, different types of feedstock apart from forestry and biowaste are used, albeit in small amounts.

In terms of fuel production, the system shifts to produce less LNG and higher total amounts of ethanol and methanol than in any other preceding scenario. I can be deduced from this that LNG is the least favorable of all three fuels, in terms of production.

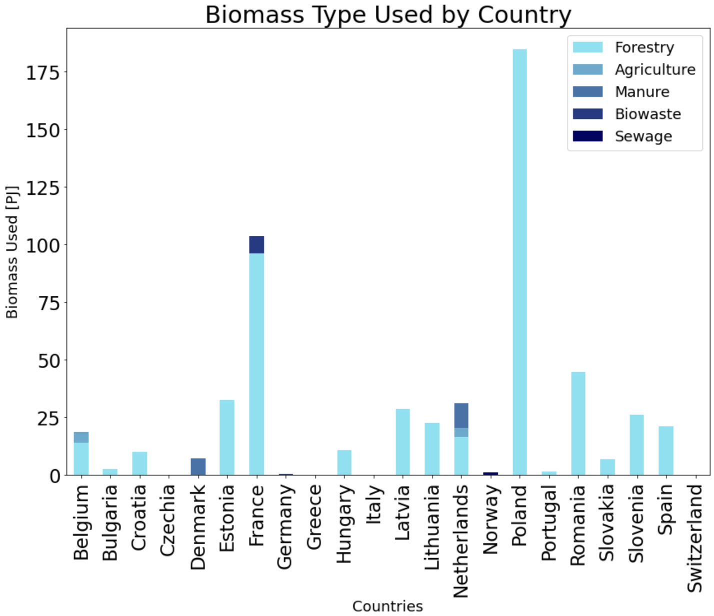


Figure 9.13: Caption

9.5. Scenario 4 - Equal Demand in all Ports, Medium Supply/Demand

So far, the energy demand has been subject to underlying assumptions regarding its distribution across Europe. Historical data on energy consumption per port creates a reasonably accurate depiction of the relative proportion that will be demanded at each in-scope port. However, this assumption takes for granted that biofuel demand is and will be proportional to historic conventional fuel demand. Though likely, this may not necessarily be the case. As explained in chapter 6, factors such as ship size, class, and route travelled will have significant effect on their adoption of biofuels. Shipping routes and ship types will in turn have effects on the locations of new bunkering hubs. For example, the EAFO list of LNG bunkering facilities in Europe [107] shows that while all considered ports have some type of LNG bunkering capabilities, the distribution is not solely proportional to fuel demand.

Therefore, to shed light on potential demand situations and how these would affect the results, a scenario is run in which the total demand remains the same as in the medium case, but is equally distributed amongst all ports.

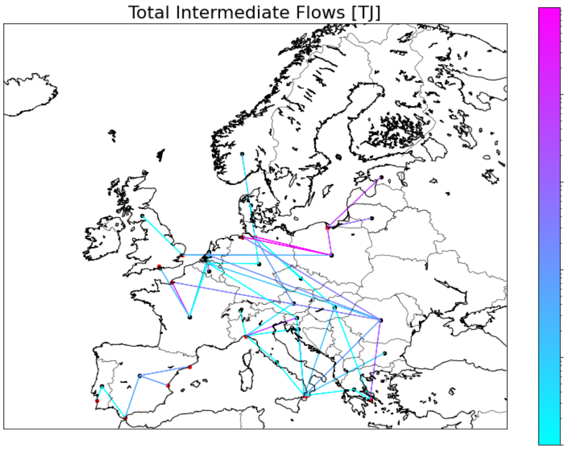


Figure 9.14: Map of total intermediate flows in Europe [TJ] (Scenario 4)

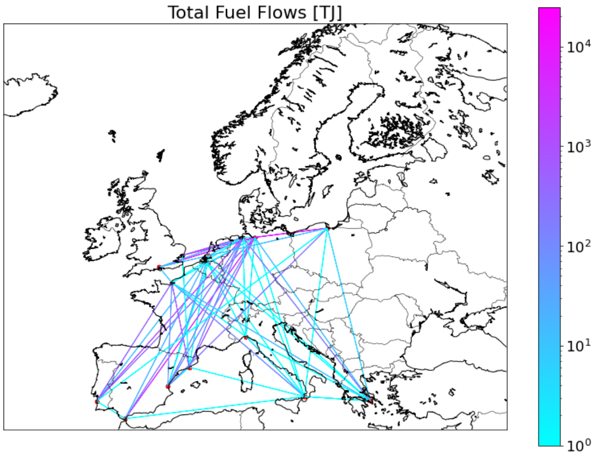


Figure 9.15: Map of total fuel flows throughout Europe [TJ] (Scenario 4)

Interestingly enough, the inland routes and quantity of transported biomass are almost exactly the same as is the base case. This makes sense, since the inland transport was originally found to make up a much larger percentage of total costs than seaborne transit. Therefore, for the same total demand, the inland routes hold more importance (in terms of costs and emissions) than the shipping pathways. The fuel shipment, on the other hand, tells a different story. Unsurprisingly, the major fuel exporters are still the largest ports such as Hamburg, Bremmerhaven, Rotterdam, Le Havre and Gdansk due to the fact that these still hold higher refining capacities. Smaller ports reduce their exports and receive the majority of their supply from the larger seaports.

The average energy costs and emissions approximate 24.5 €/GJ and 30.8 kgCO_2/GJ. This is reflected in a slightly upward shift of the marginal cost curve compared to the base case.

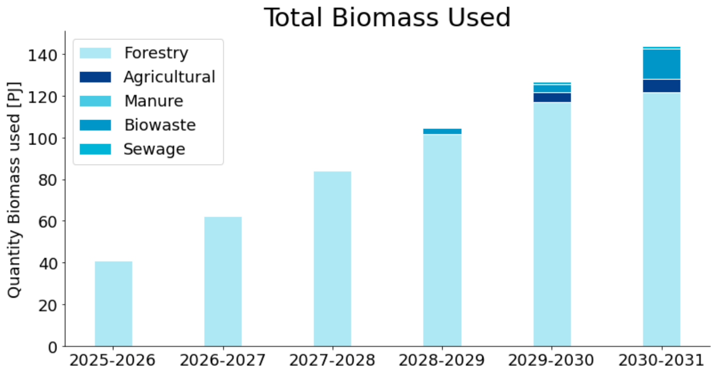


Figure 9.16: Caption

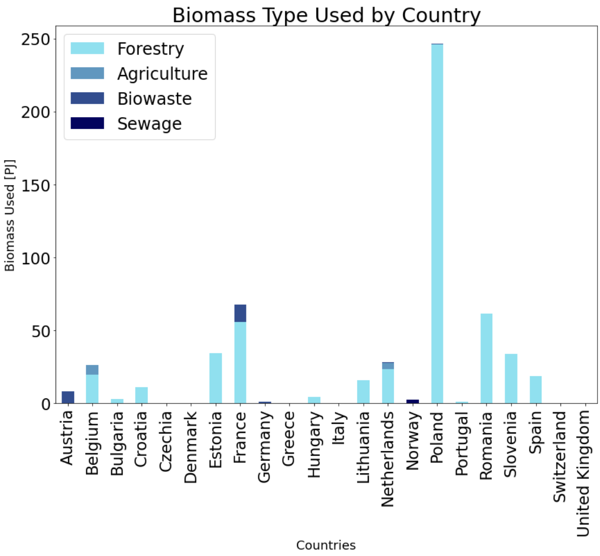


Figure 9.17: Map of total intermediate flows in Europe [TJ]

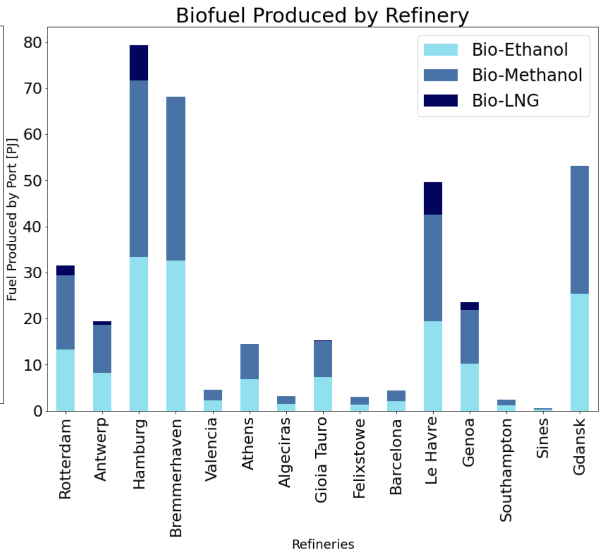


Figure 9.18: Map of total fuel flows throughout Europe [TJ]

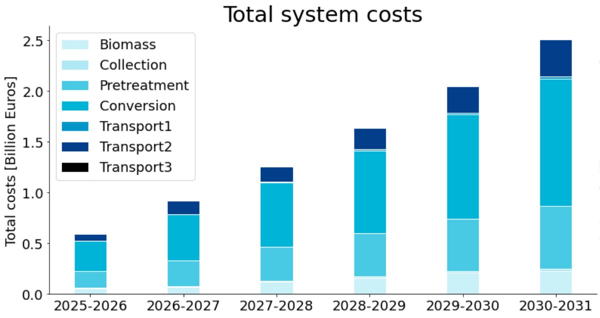


Figure 9.19: Map of total intermediate flows in Europe [TJ]

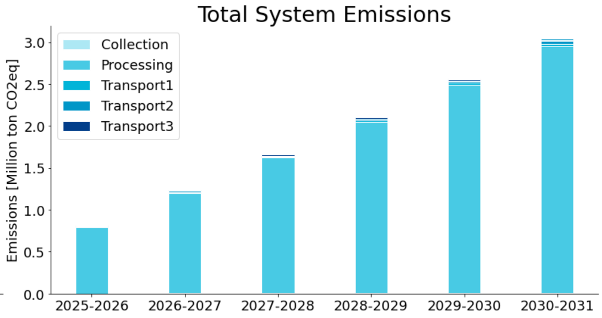


Figure 9.20: Map of total fuel flows throughout Europe [TJ]

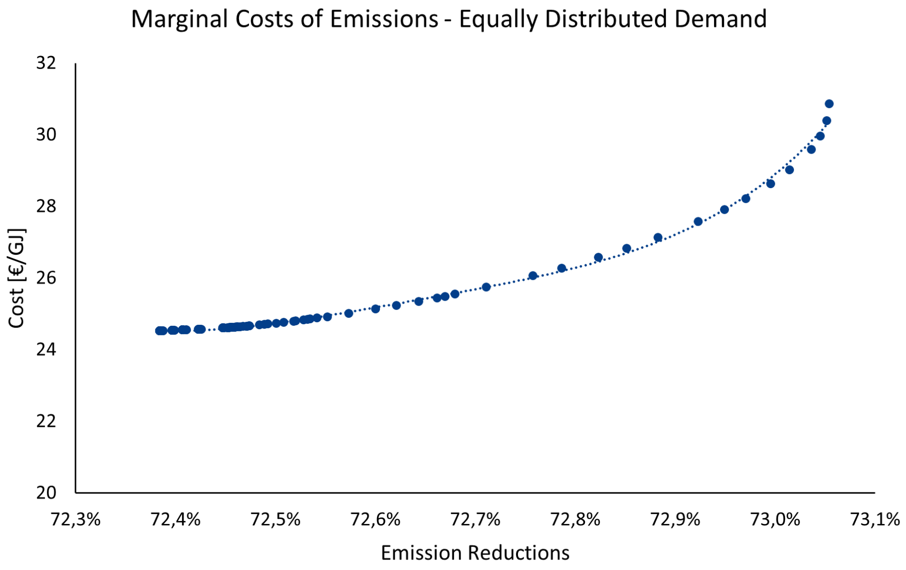


Figure 9.21: Marginal cost of emissions equally distributed demand (Scenario 4).

9.6. Scenario 5 - No Refining Capacities Constraint, Medium/Equal Demand Medium Supply

The objective of this scenario is to determine the behavior of the model when the most frequently present constraint (refining capacity) is omitted. Within this scenario, two separate cases of demand will be observed, namely; medium demand and equal demand. The medium demand instance serves to see how the system reacts considering the port sizes and respective demands. The equal demand distribution is also shown to intentionally disregard port sizes and energy consumption, so the model can be observed purely from a geographical standpoint. Essentially, the total amount of fuel to be delivered is the same in both cases, only the distribution changes.

The amount of biomass collected is shown in 9.24 and is the same for both the equally distributed and conventional demand settings. Again, almost all collected biomass are forestry residues. A tiny amount of biowastes is also collected in Belgium and The Netherlands, most likely due to the nearby vicinity. The countries from which the forestry residues are collected are all countries with relatively high supplies and low prices, even if the distance is comparitively far. The intermediate product flows for both demands are also identical. Of the 12 countries where biomass is collected, the majority flows to Antwerp except for the biomass collected in Slovenia and Croatia, which instead go to Genoa. It seems slightly unusual for the feedstock to travel to one or two ports in specific instead of just travelling to the nearest port. Since per kilometer travelled and gigajule transported, shipping is more efficient than road transport, it would seem logical to first travel to the the nearest refinery, and then balance out any deficits through freight routes. However, upon testing this scenario under several circumstances, this only happens for other biomass types. Wood seems to have a good balance between its dry LHV and its dry density making it a great candidate for inland route transit. Since the trucks are limited by cargo volume, with wood, a larger energy content can be transported than any other feedstock. Therefore, the costs are associated with transporting the biomass to Antwerp are offset by the decrease in costs associated with exporting from a strategically located port.

In terms of fuel production and distribution, ethanol and methanol are created in equal amounts. LNG is produced but almost at a negligible amount. However, at environmental/economic weights of 1-0 (only environmental objective function), the only fuel produced is bio-LNG.

Since the majority of biomass is transported to Antwerp, the majority of the fuel is shipped to the remaining ports from there. The main difference in fuel shipment between the equally distributed and conventional demand distributions is that in the conventional, Genoa exports to more southern ports since, overall less energy is needed in the south. Further, in the equal demand distribution, the outward flows from Antwerp are mainly the same.

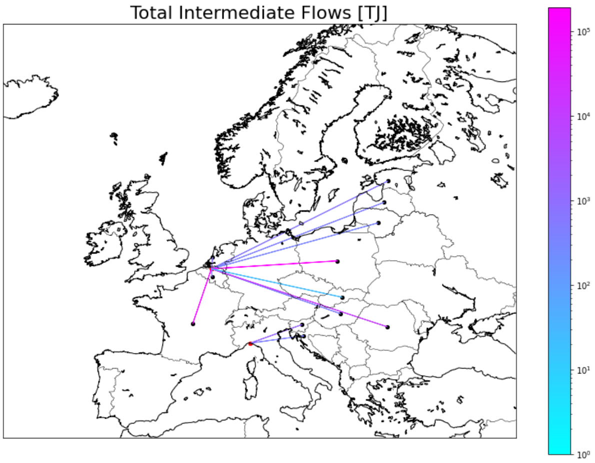


Figure 9.22: Biomass flows with no refinery constraint, equal/medium demand (Scenario 5) [TJ]

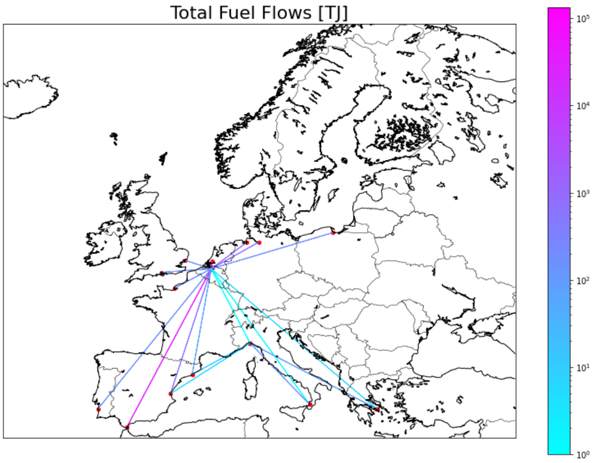


Figure 9.23: Fuel flows with no refinery constraint, medium demand (Scenario 5) [TJ]

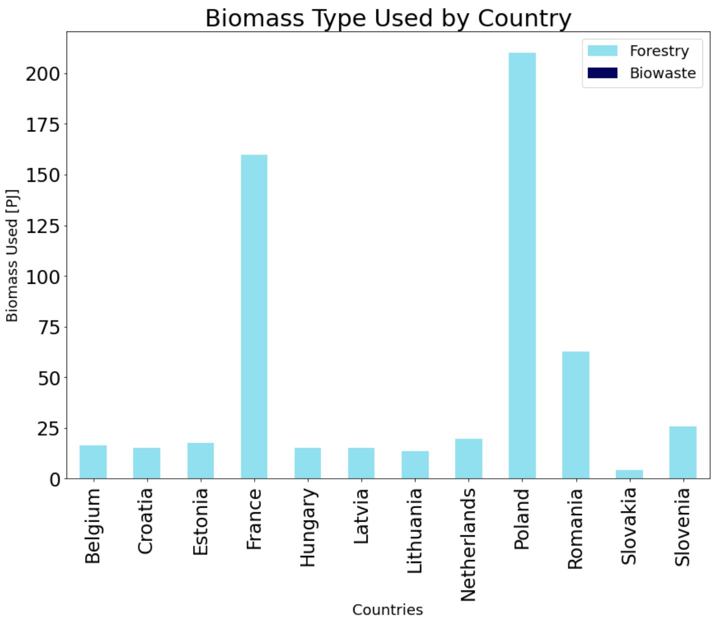


Figure 9.24: Amount of biomass used from each country [PJ] (Scenario 5).

Predictably, the total costs and emissions for this scenario are the lowest developed yet. The average price and emissions are 22.94 €/GJ and 30.93 kgCO_2/GJ. The marginal costs are displayed in figure 9.25 which shows a slight, yet noticeable price difference between this scenario and the base case. In this scenario, emissions can be reduced to a larger extent (73.6%) albeit at a very high cost.

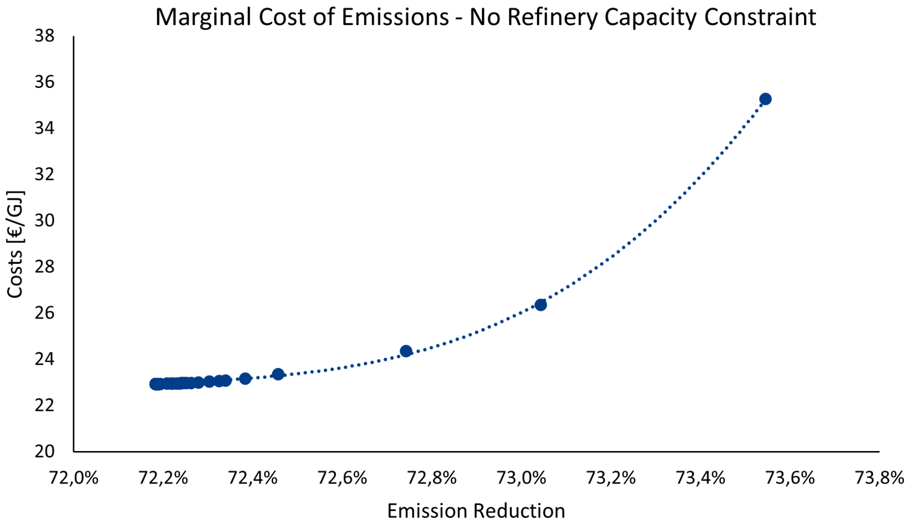


Figure 9.25: Marginal cost of emissions (Scenario 5).

9.7. Scenario 6 - Each Fuel Separately, Medium Demand Medium Supply

Each fuel outlined in this report is a potential future shipping propellant candidate. Apart from the costs and emissions involved in the supply chain of the fuel, their adoption likelihood depends on factors outside the scope of this study. In the case that for some external circumstance the viability of one fuel becomes compromised or one becomes more preferable than the others (e.g. a specific feedstock import from outside Europe becomes available/cheap favoring a specific fuel, a new engine technology allows for cheaper and faster retrofitting to a specific fuel, etc.), the model will be run for each fuel separately. Ultimately, this will help understand which feedstocks and countries are better suited for what fuels, which fuels can actually meet the energy demand and what costs and emissions would be associated in each case. The same constraints, capacities and yields apply, but isolating each case.

Bio-Ethanol

In the case of solely using ethanol to fulfill the energy demand, the fuel itself is not enough. However, this is due to capacity limitations, not lack of feedstock. Figure 9.36 clearly shows that for the production of ethanol forestry is largely preferred, though a very small amount of biowaste is sourced in the Netherlands. The distribution of production is largely shared amongst all refineries, and since all are operating at their full capacity, figure 9.27 reflects port bio-ethanol capacities.

The total costs and emissions are very similar to what is seen in other scenarios. The most apparent difference is the (relative) increase in transport 2 costs and the decrease in processing costs. As stated earlier, ethanol is the cheapest fuel to produce in terms of the conversion process. However, it is dificult to make a comparison in terms of total costs (with other scenarios) due to the fact that a shortfall of 0.156 EJ was realized. The ports with the biggest deficits in descending order are: Algeciras, Rotterdam, Antwerp, Sines, Valencia and Felixstowe. The ports that permitted deficits did not have any imports of fuel. Overall the fuel flows between ports were much smaller than in any other case, and the number of travelled shipping routes, notably lower.

Bio-Methanol

Bio-methanol is the only case of the three fuels in which the infrastructure allows for complete energy demand satisfaction (under a medium demand and supply scenario). Again, for this fuel, the preferred feedstock is forestry residues, though a significant portion of manure from the Netherlands and smaller amounts from Denmark, Germany, Italy and Portugal are used. Unlike ethanol, the refining of bio-methanol is less distributed, and takes place in the northern sea ports. A smaller proportion is converted in Le Havre and Genoa.

Solely using methanol would incur significant cost and emission increases, in specific a 53% increase in costs and a 20% rise in emissions compared to the base case. This would mean an average production price of 37 €/GJ setting it at almost three times the average cost of traditional fuel options. The total emissions would

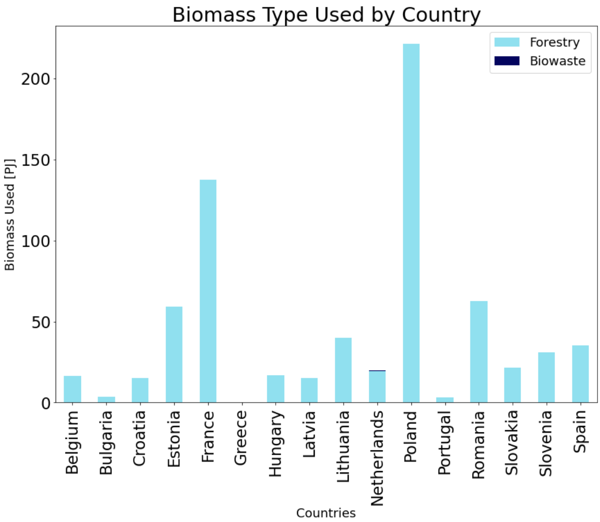


Figure 9.26: Biomass used for production of ethanol [PJ].

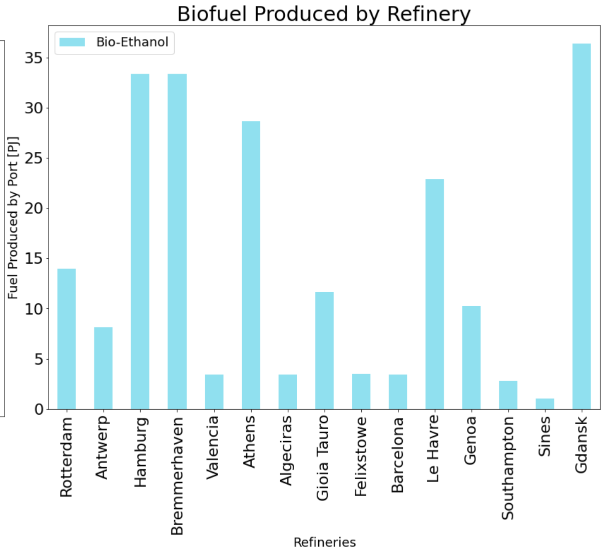


Figure 9.27: Refinery output for production of bio-ethanol [PJ].

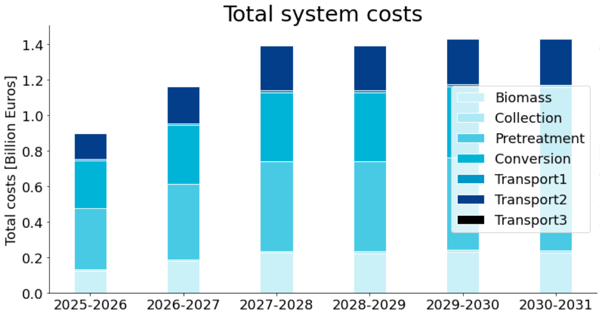


Figure 9.28: Total costs for production of ethanol [billion euros].

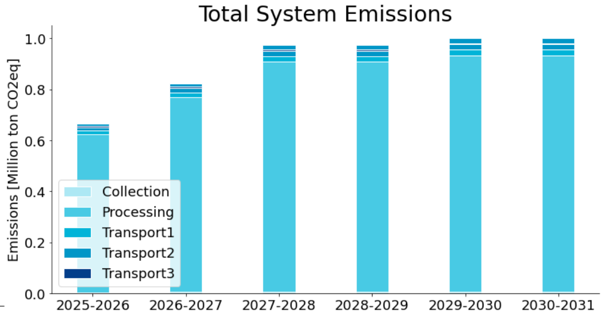


Figure 9.29: Total emissions for production of ethanol [million ton CO_2eq].

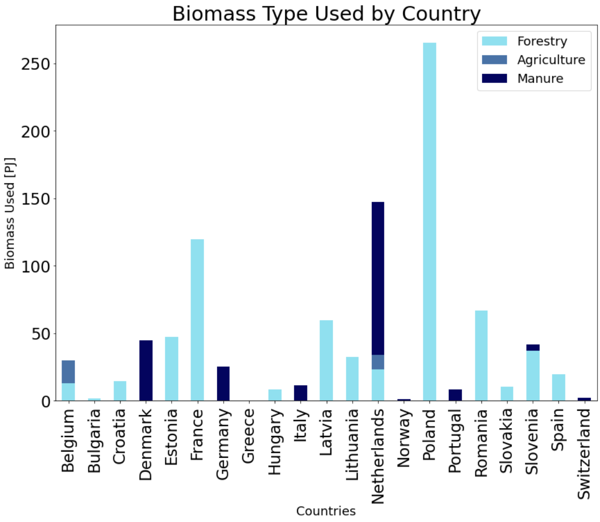


Figure 9.30: Biomass used for production of methanol [PJ].

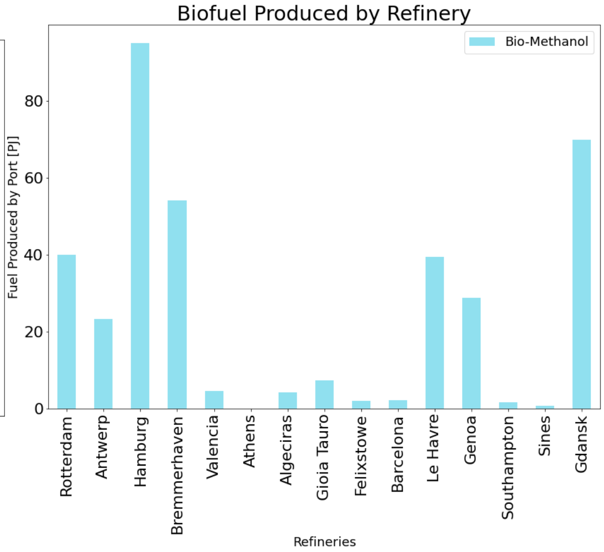


Figure 9.31: Refinery output for production of bio-methanol [PJ].

amount to 13.8 billion tons of CO_2eq or an average of 37 $kgCO_2eq$/GJ.

In the case of methanol, it is also possible to see how altering demand levels affect the biomass selection

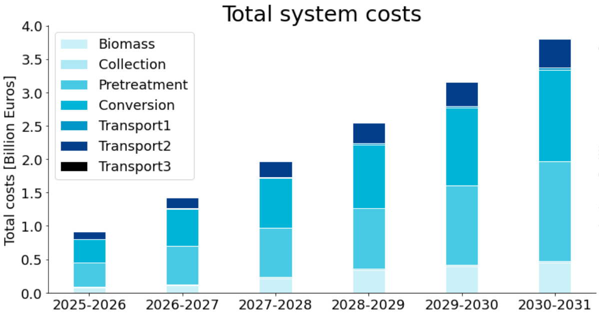


Figure 9.32: Total costs for production of methanol [billion euros].

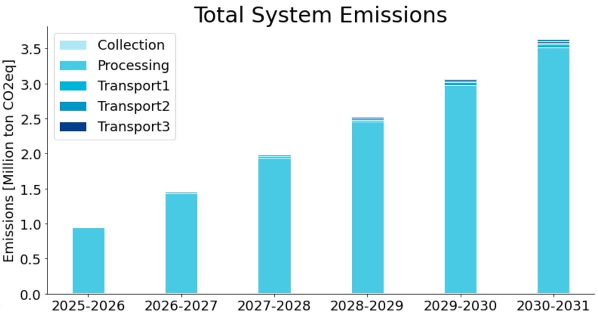


Figure 9.33: Total emissions for production of methanol [million ton CO_2eq].

and the source countries that are used as suppliers. As can be shown through images 9.34 and 9.35, the inland routes seem much shorter and proximal than in other cases. In the first years, when the demand is below a certain threshold, the costs and emissions associated with transporting forestry products from countries such as Poland and Bulgaria outweigh is more optimal than collecting biomass from closer sources, despite the large distance between eastern European countries and North German ports. However, as the years progress and the demand increases, it becomes more optimal to use manure from countries such as the Netherlands, Denmark, Germany and Italy, which are closer to the ports.

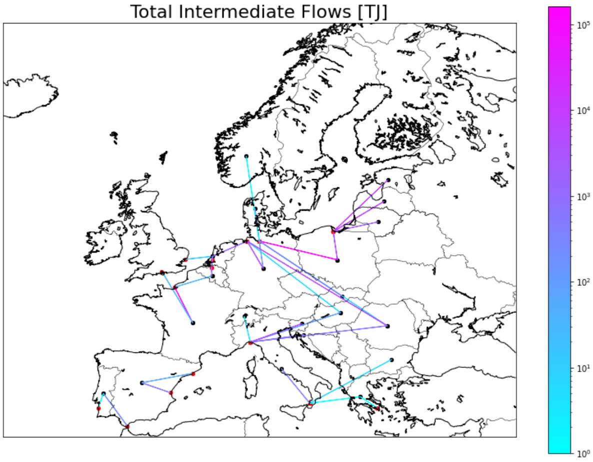


Figure 9.34: Biomass used for production of methanol [PJ].

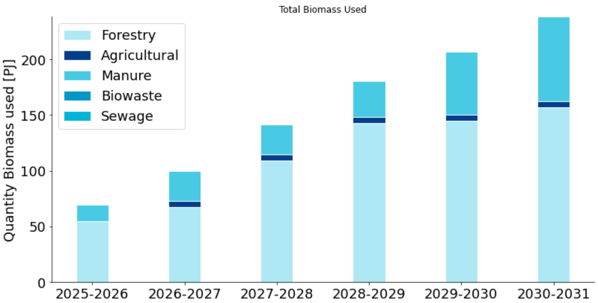


Figure 9.35: Refinery output for production of bio-methanol [PJ].

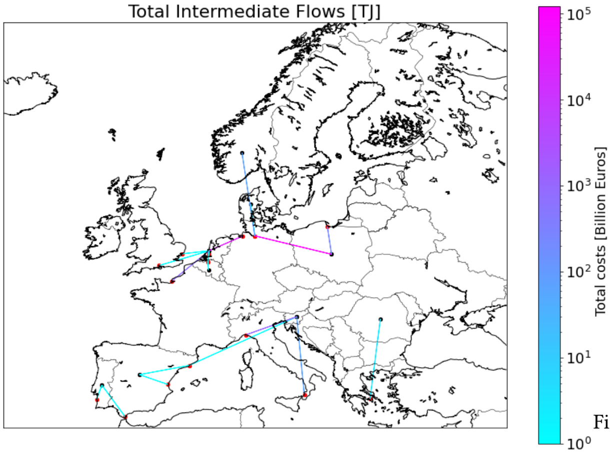
Bio-LNG

The refining for bio-LNG is done almost completely in Germany and shipped out from the two ports. It can be seen from the deficit, that the production capacities are way below the demand. However, the preferred feedstocks fo the production of LNG appear to be forestry residues, which are collected at any point, and manure, which is only collected in countries with proximity to ports such as the Netherlands. This hypothesis was also tested by increasing the production capacity to accommodate for the full demand, and the trend held. Manure from Denmark, Belgium, Germany and the Netherlands (in increasing order) was used to produce LNG in Antwerp.

The total costs and emissions average out to 32.35 €/GJ and 29.7 gCO_2eq/GJ, respectively.

	2025-2026	2026-2027	2027-2028	2028-2029	2029-2030	2030-2031
Rotterdam	0	0	0.1	6.43	12.97	19.66
Antwerp	0	0	5.89	7.49	9,13	10.80
Hamburg	0	0	0	0	0	0
Bremmerhaven	0	0	0	0	0	0
Valencia	0	1.77	2.39	3.03	3.69	4.36
Athens	0	0.74	1.05	1.37	1.70	2.03
Algeciras	0	7.08	10.86	13.75	16.69	19.7
Gioia Tauro	0	0.35	0.66	0.98	1.31	1.64
Felixstowe	0	0	1.03	1.37	1.70	2.03
Barcelona	0	0.35	0.98	1.50	1.83	2.17
Le Havre	0	0	0	0	0	0
Genoa	0	0	0	0.03	0.36	0.7
Southampton	0	0	0	0.62	1.27	1.94
Sines	0	0	1.13	1.45	1.78	2.11
Gdansk	0	0	0.27	0.59	0.91	1.25

Table 9.2: Deficit as a funtion of port and year for LNG [PJ]



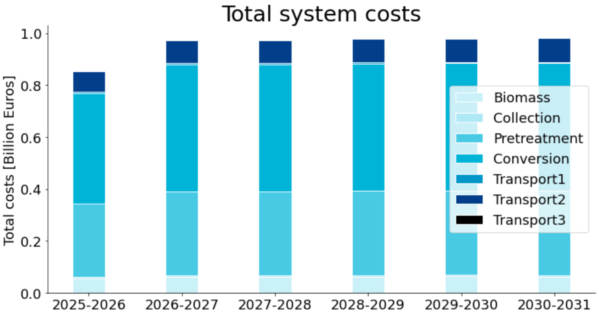


Figure 9.37: Total emissions for production of LNG [ton CO_2eq].

Figure 9.36: Total costs for production of LNG [billion euros].

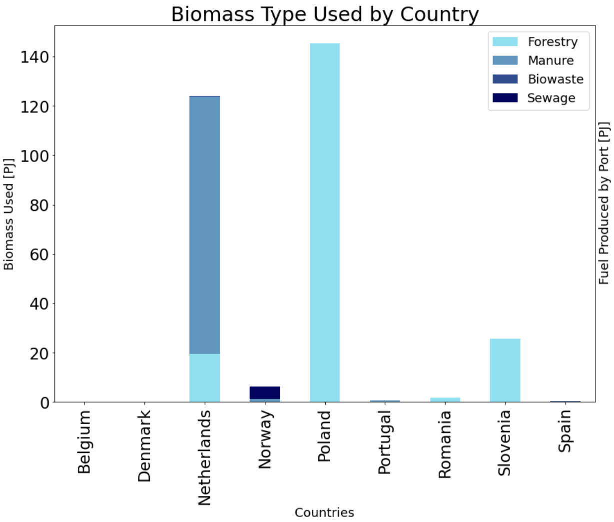


Figure 9.38: Biomass used for production of LNG [PJ].

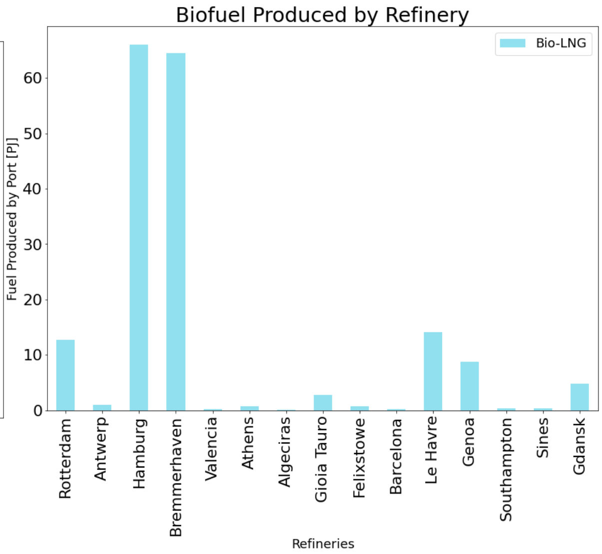


Figure 9.39: Refinery output for production of bio-LNG [PJ].

9.8. Analysis of Results

In this section, the results from all scenarios are collected and analyzed to form any conclusions while taking into account the specific conditions for each scenario.

9.8.1. Costs and Emissions

Throughout the studied scenarios, the relationship between the costs and emissions has changed for each condition. Though It's largely based off of the cost of emissions which haven't been altered, the different circumstances in each scenario have resulted in a set of unique results. Each scenario holds different values in terms of specific costs, specific emissions, and the ratio of the two. Looking into each of these results gives insight into how and why the system changes and how they compare.

On average, one MJ of created product carries around 27.75 gCO_2eq with it and costs 28.61 to produce. The average specific system costs over time are displayed in figure 9.40. It can be noticed from the graphs that in general, the specific costs for each scenario only slightly increase over the entire time-period. The medium and low demand scenarios (base case, scenario 3 scenario 4, scenario 5) all lie within a very close range, which is to be expected considering the similar conditions. The specific costs of the each fuel alone is shifted upwards from the low/medium demand scenarios, heavily hinting the fact that a combination of the three fuels is more preferable than any one fuel on its own. The scenarios which carry high demand stand out from the rest in their irregular nature. Instead of increasing or remaining constant during the whole period, they are marked by an abrupt plateau in 2027. At this point, both situations reach an upper-bound on the total amount of fuel that can be produced, and thus the system remains the same (for the most part) in the ensuing years. The situation marked by the lowest average energy costs is seemingly the scenario in which the capacity constraint is omitted. Surprisingly, the reduction in average costs seems not to be so significant from the medium-demand. However, since these are specific costs, and when talking about a large amount of product flows, this small change in specific costs results in a large disparity between the total costs. The specific emissions, shown in figure 9.41 tell a similar story to the costs. However, for the majority of cases, the specific emissions remain almost constant throughout the entire time period. As was discussed in the sensitivity analysis and base case, the emissions are dominated by the conversion phase, which is marked by the unit conversion emissions. These values, though specific to each fuel and feedstock, remain constant over time. Ultimately, what determines the emissions is the fuel produced. As can be seen, ethanol has the lowest emissions, and methanol the highest. LNG falls between the two. By combining the three fuels in specific quantities, the right trade-off between costs and emissions can be reached.

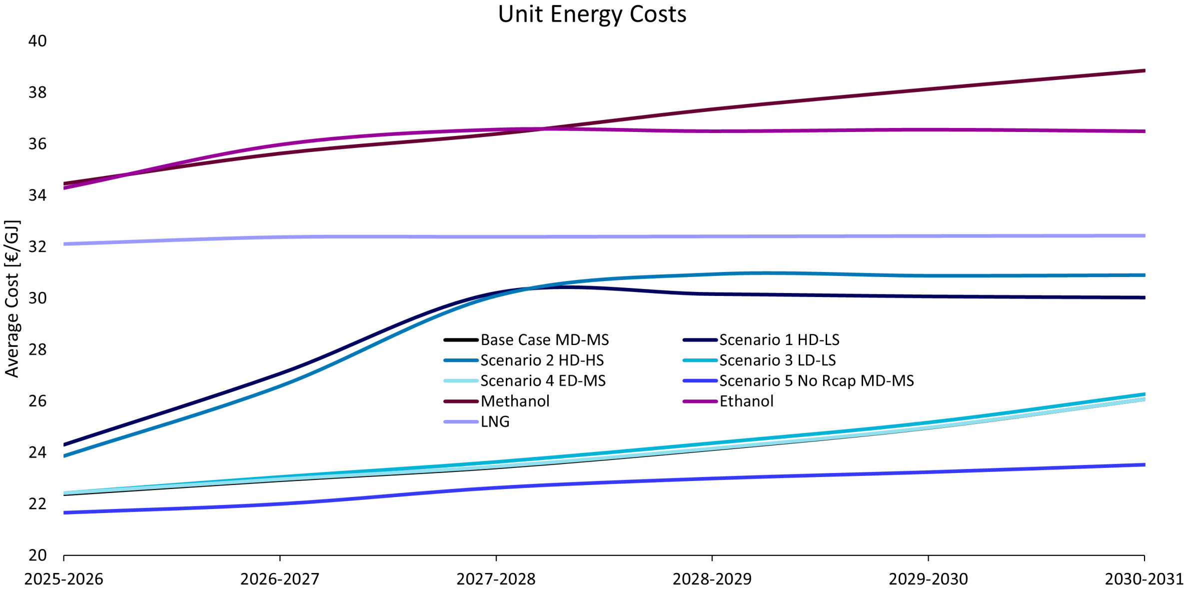


Figure 9.40: Unit energy costs as a function of time for all scenarios.

In terms of the marginal costs, not all scenarios are comparable. In specific, the scenarios in which a deficit is allowed display chaotic and impractical marginal cost curves as a result of the compromise between the cost

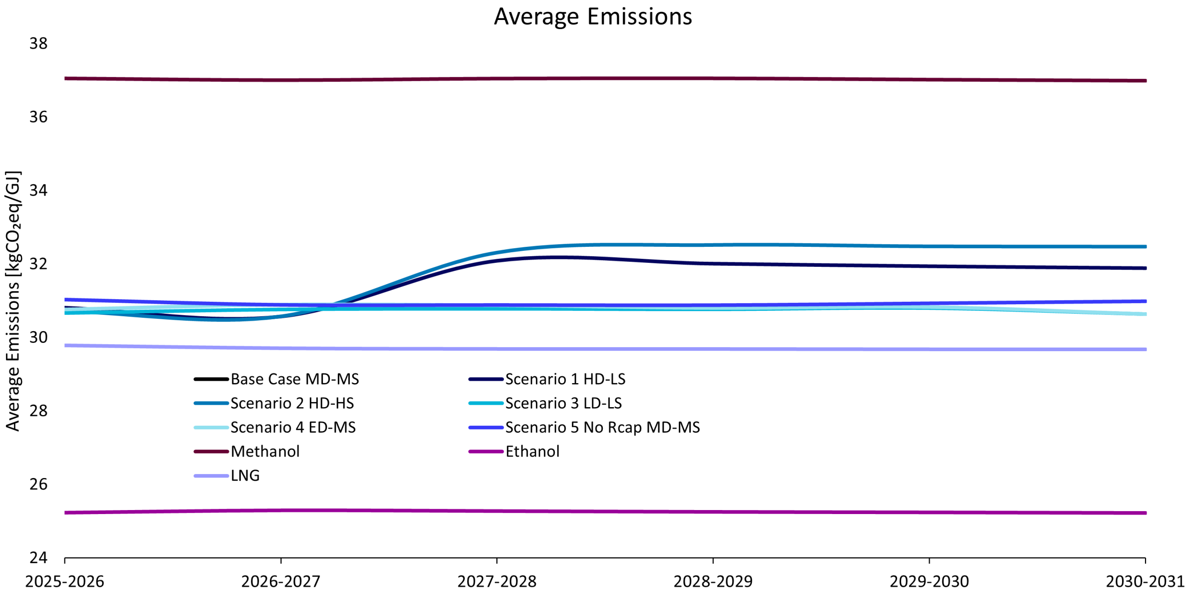


Figure 9.41: Caption

of having a certain deficit and the cost of meeting a demand. For example, the high demand scenarios have a range of costs of as low as 15 €/GJ for the same or even larger reduction of emissions as in the base case. This is not a fair comparison, as whenever a deficit is allowed, the system can just opt to remove any production lines that are too costly and pay the price of the deficit, which can be much cheaper. Therefore, only the marginal cost curves of scenarios with full demand satisfaction (no deficit) will be compared.

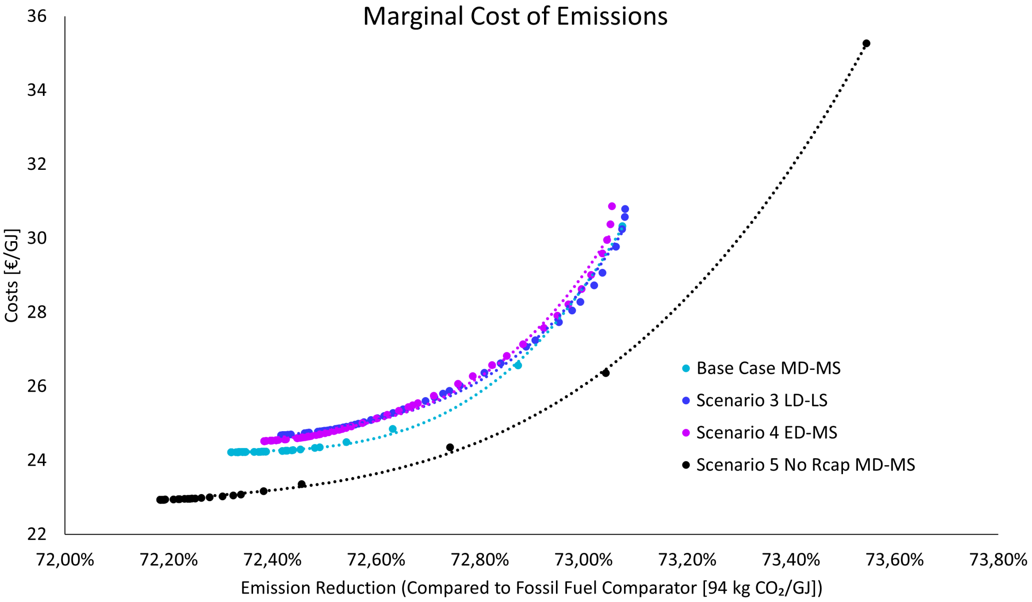


Figure 9.42: Caption

The figure shows that even for the different scenarios, the range of emission reduction is quite similar. Again, this is a result of emission distribution, which is prevailed by the conversion process. This is also highlighted in figure 9.44. The main difference in the scenarios is therefore the cost associated with the emission abatement. As can be seen, the majority of the scenarios fall within the same spread, ranging from costs of 24-32 €/GJ and an emission abatement range of 23.3% to 73.1%. The only condition that differs from the norm is Scenario 5, in which the refining capacities were omitted as a constraint. This set-up allows for a broader range of emission reductions and a lower average cost.

The distributions of costs and emissions for each scenario are displayed in graphs 9.43 and 9.44.

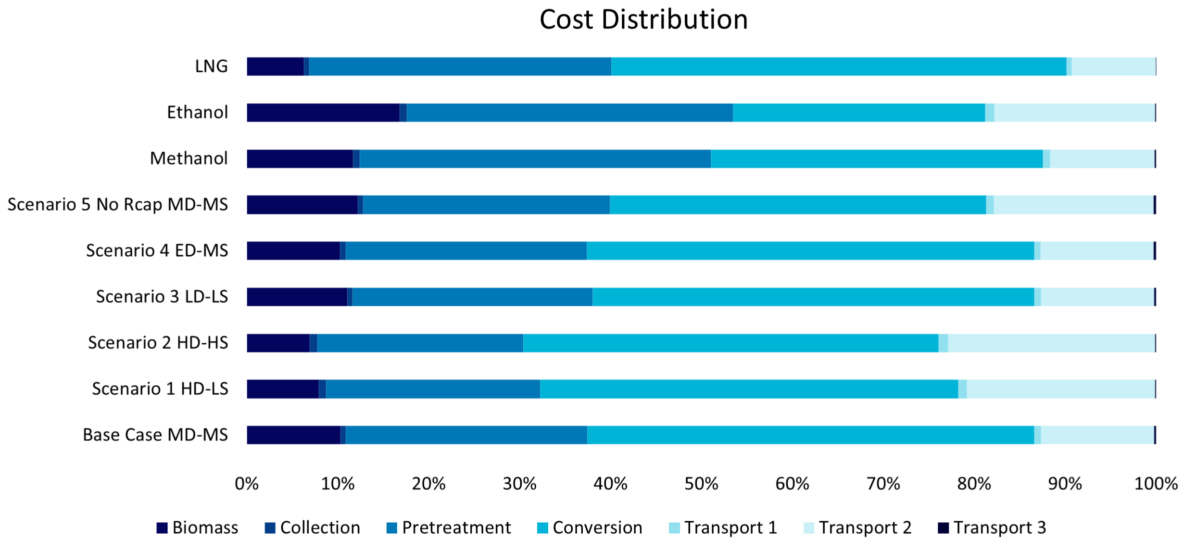


Figure 9.43: Cost distribution of all scenarios.

The pre-processing and the conversion together make up more than half of the total costs in almost every scenario, though the biomass itself and the second leg of transport also make up significant portions. On average the conversion takes up 44% of the total costs and the pre-treatment 28%.

The biomass costs, on average, are lower for scenarios with higher demands, as the system turns to use cheaper and wetter feedstocks such as sewage, biowaste and manure which have lower (if any) costs compared to agricultural/forestry. In the case of LNG, the biomass costs are also very low due to the fact that a large proportion of the feedstock used is biowaste (see figure 9.38). The collection costs are almost negligible as in all scenarios this costs doesn't surpass the 1% of total costs. The first transport cost is also very minimal, only reaching over 1% of total costs in one scenario, the same is true of the shipping costs. On the other hand, the second leg of transport accounts for a much larger share of the costs, ranging from 10-20% depending on the run conditions. The cost of inland transport depends on a combination of feedstock preference, proximity to refinery and the demand/supply setting as well as any additional conditions. There is no obvious consensus or pattern with regards to the transport 2 costs as these are traded-off with a multitude of other factors. One thing that can be said however, is that the cost fraction is usually low when the demand is medium to low. Higher demands usually lead to the use of sub-optimal road routes and use of feedstocks that have low specific and volumetric energies, quickly raising the relative proportion.

The emissions, as opposed to the costs, are almost completely dependent on the conversion of raw biomass to final product (figure 9.44). The inland road transport (in particular the second leg) does hold some small weight, but ultimately, the step which holds the largest emission reduction potential is the conversion of primary to final product. Usually, in the production of fuels, the supply chain is much larger and more distributed resulting in larger proportions of emissions in the transport. For this supply chain, which is produced locally in Europe, all distances are relatively small compared to the supply chains of oil products, which can span more than half the globe through the entire process. For this reason, it makes sense for the emissions to be so concentrated in the processing segment.

Another, more detailed way of viewing the costs and emissions, is by dividing them into the production-line segments and comparing separate scenarios. For example, in figure 9.45, the specific energy costs of each supply-chain segment are displayed for all scenarios. At each segment, the cost associated with that stage is divided by the energy content associated with that stage. So, for example, for the specific biomass cost, the total expenses are divided by BU, the biomass use, and the sea transport costs are divided by SF, the amount of shipped fuel. In other words, the price at each stage is relative to the product being considered at that stage. This makes the specific costs/emissions more accurate (as opposed to just using total fuel energy produced).

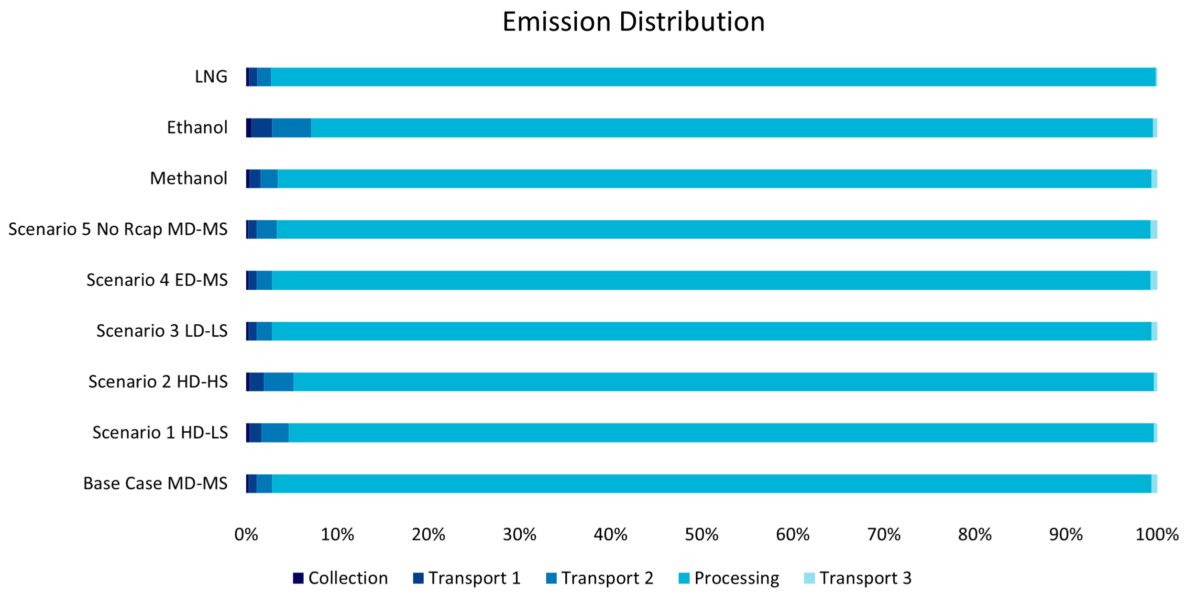


Figure 9.44: Emission distribution of all scenarios.

Much can be said with respect to the first figure. To start, the specific biomass costs for all scenarios fall within a very tight, low range. Depending on the type, year, and country, biomass costs can range from zero to 9.35 €/GJ, so it is interesting to see that the range is so similar and low for all scenarios. This appears to indicate that both the type of biomass as well as the country of origin (not only geographically but in terms of price-level) were substantial determinants in biomass selection. The collection, first leg of transport and third transport leg all incurred little-to-no costs alike. In the pretreatment phase, which suggests most about the type of feedstock used, methanol holds a strong advantage, while ethanol and specifically LNG are the most expensive. The scenario costs associated with converting are ordered in a similar way; LNG as the most expensive, ethanol as the least, and methanol is somewhere between the two. For the inland transport costs, there seems to be a tradeoff, for fuels such as LNG which are mainly comprised of wet, cheap biomass, the transporting costs are higher but the routes are shorter allowing a reduction of costs. On the other hand, other scenarios, expecially those with higher demands, will use drier feedstock but collect them from further sources, increasing the costs.

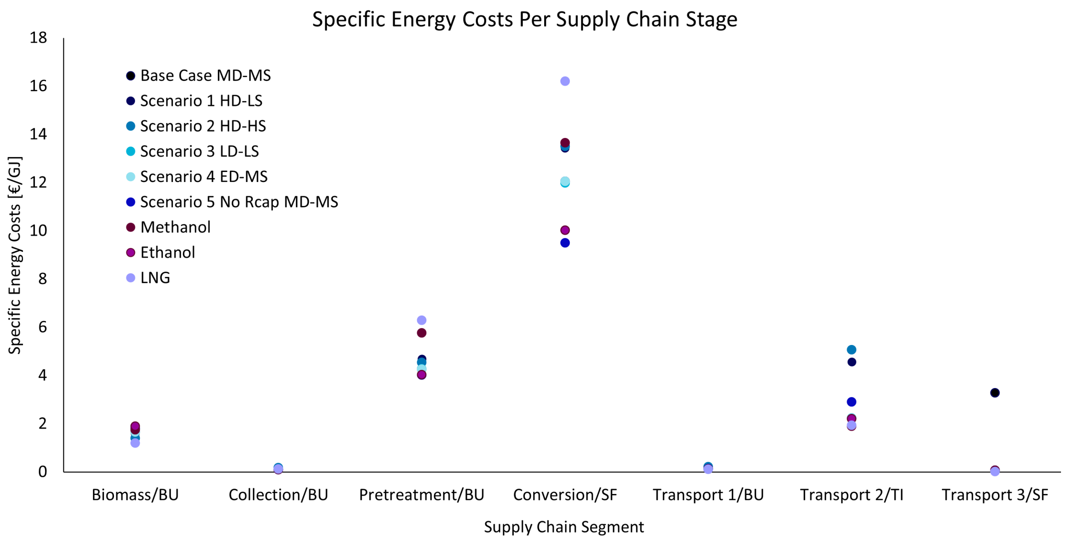


Figure 9.45: Caption

The emissions by supply-chain segment are displayed in figure 9.46. In the case of emissions, the axis of the chart is displayed on a logarithmic scale, due to the large difference between processing emissions and all other phases. The processing emissions tell us mainly what was already discovered. Ethanol has the lowest emissions per unit of product generated, followed by methanol and ethanol. Situations in which the demand is lower or the supply of biomass is high are more favorable than those with high demand, as more of the optimal biomass type for each fuel is available. It is noteworthy to mention that for the shipping emissions, LNG holds the lowest specific emissions.

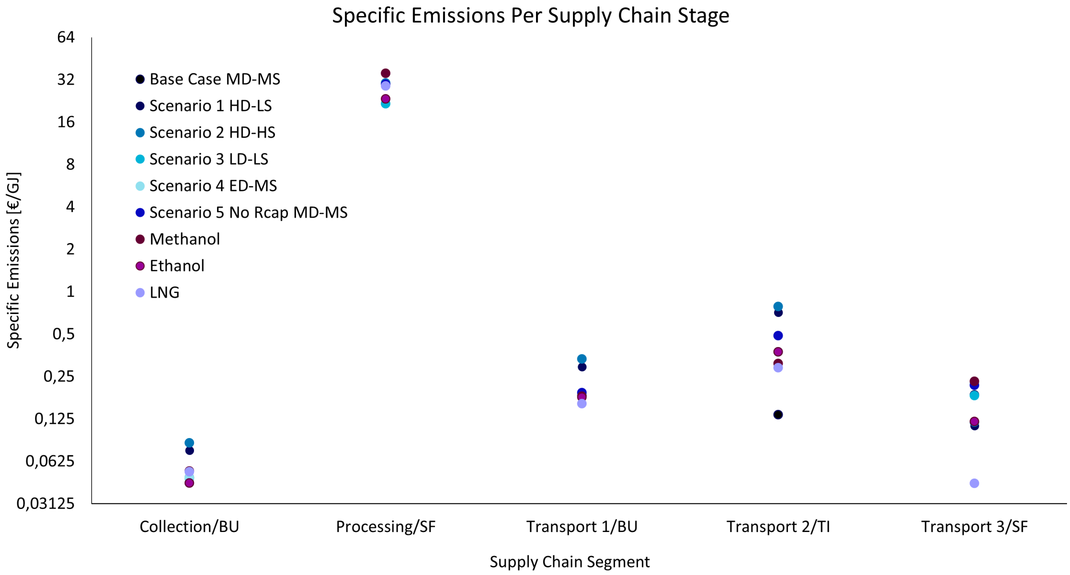


Figure 9.46: Caption

9.8.2. Biomass Use and Fuel Production

One of the main research questions of this report is to determine the suitability of the available biomass types, from where and for what. To do so, the outputs regarding the use of biomass will be compiled and evaluated to reach any conclusions in this respect.

Figure 9.47 displays the total use of each biomass type per scenario. Figure 9.48 shows the country of origin and total quantity of biomass used in each scenario. Finally, image 9.49 shows the normalized biomass sourcing in terms of biomass type. In other terms, the graph shows the proportion of biomass type taken from each country expressed first as a fraction of all biomass collected in a scenarios, and then divided by 9 (9 scenarios). Ultimately this shows the probability of a biomass being sourced from a country and being of a particular kind for the explored scenarios.

From the graphs, it becomes apparent that forestry residues are by far the most popular feedstock choice, and this is true in every scenario. Livestock manure comes in at a far second with in total about 10% of the use of forestry residues. Agricultural byproducts also make up a significant portion of the supply, especially in cases where the demand is high. Biowaste and sewage are used mainly in scenarios in which the supply and demand locations are within a small distance of each other. In many cases, almost all of the available supply of forestry residues is used up, heavily hinting their preference. However, as was seen from the yearly biomass use for each case in the scenario analysis, it is a combination of the biomasses that is preferred and not just the use of one entirely and then the next. This means that each country is better suited to provide a specific type of biomass under each scenario.

In terms of the biomass origin, the vast majority is collected from Poland in the form of forestry residues. This is due to three main reasons, namely; the proximity of Poland to the strategic northern ports of Germany, Belgium and the Netherlands, the high supply of forestry residues (only Sweden, Germany, Finland and France have higher supplies) and the cheap costs in Poland (only the Netherlands and Romania have lower costs). However, a significant portion is also collected in France, the Netherlands and Romania. A large factor that played into the biomass sourcing selection was the price.

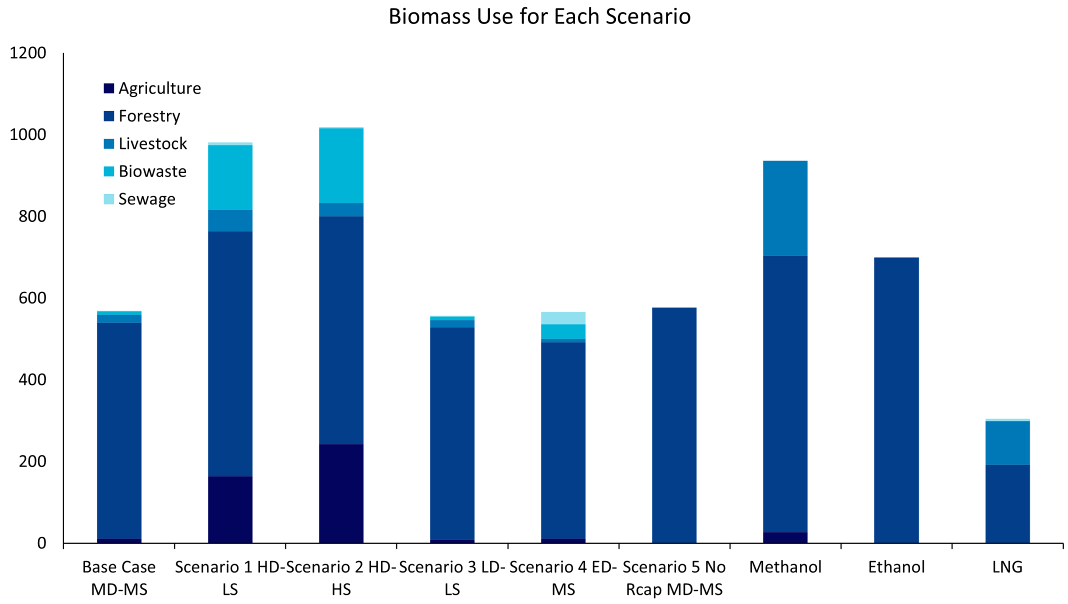


Figure 9.47: Use of biomass by type in each scenario.

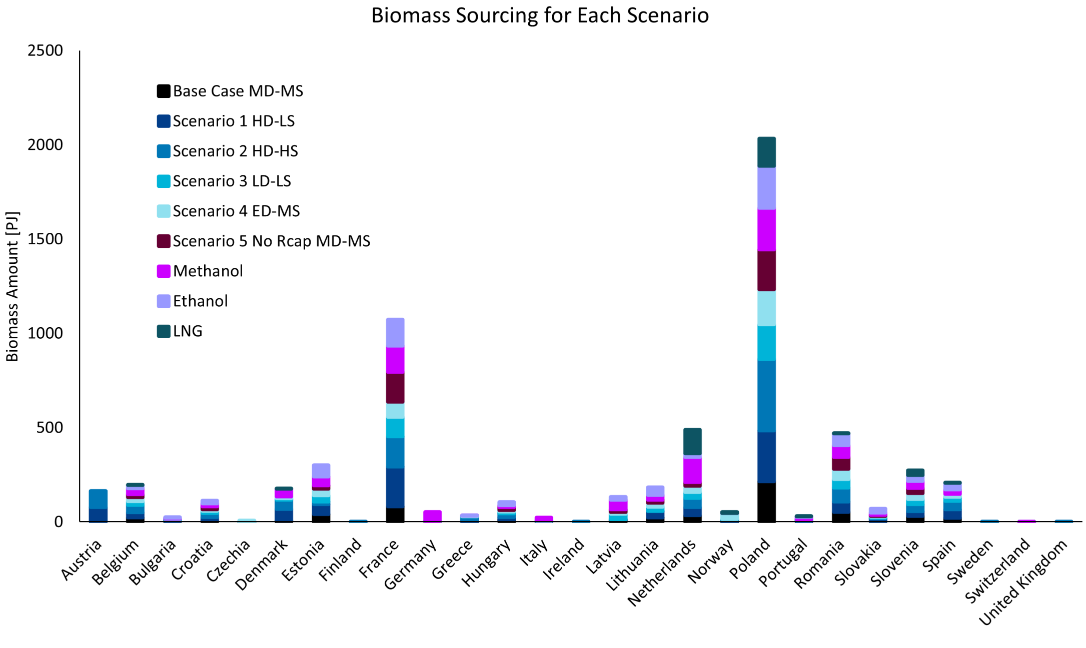


Figure 9.48: Biomass sourcing.

The fuel production by percentage is shown for every port and in total for the outlined scenarios (figure 9.50). As can be seen, ethanol and methanol are very close in terms of relative production, however, overall methanol has a higher uptake.

9.8.3. Inland and Seaborne Routes

Another main output of the model was the optimal routes between collection sites, refineries and ports. Both the intermediate and fuel flows have been shown for almost all scenarios separately. This is done for all biomass types and all fuels, in separate graphs. Graph 9.51 not only shows who the biomass suppliers are, but also the routes that are taken in preferential order. The darkest shaded routes originating from the same country are usually the ones that are first used, then when capacity constraints arise, the next options are taken. The same goes for figure 9.52 except for the ports. However, the routes are mainly based on port-specific scenario

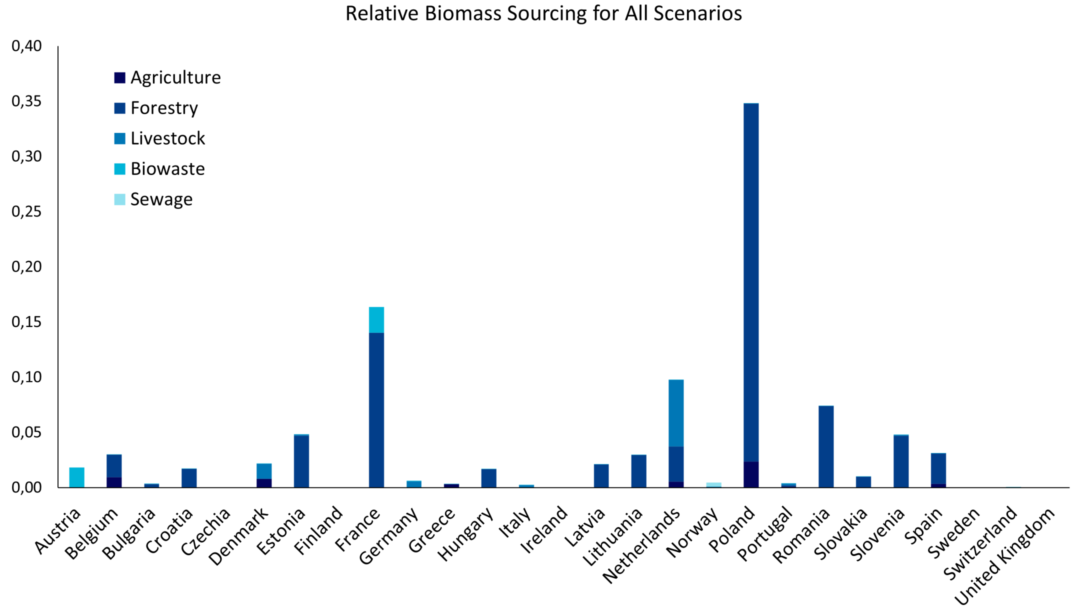


Figure 9.49: Total relative biomass sourcing.

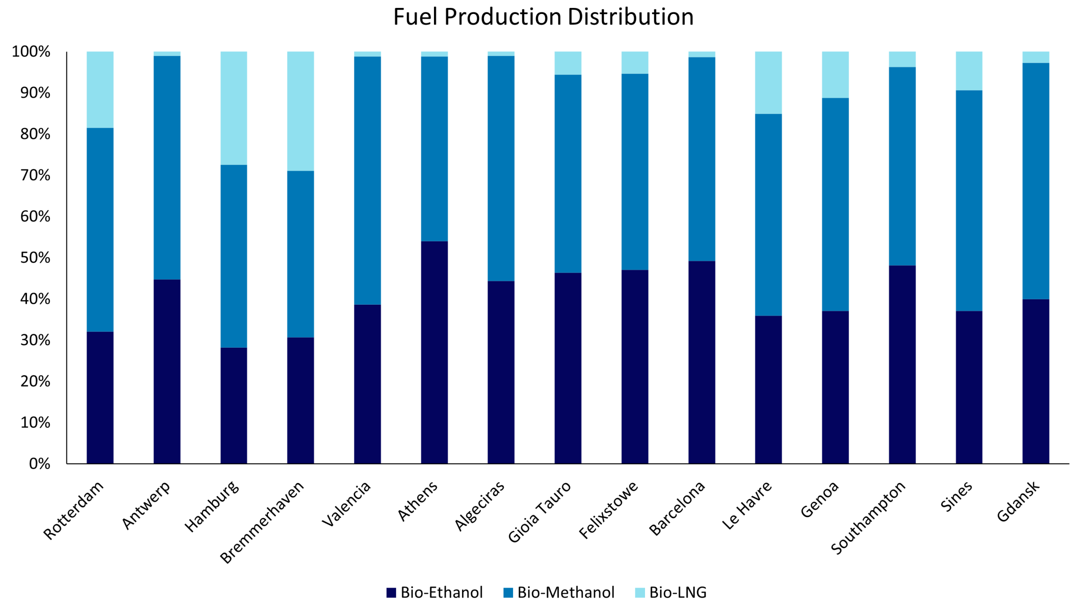


Figure 9.50: Relative fuel production by port.

demand. As can be seen, the vast majority of fuel originates from the north, mainly Germany, the Netherlands and Antwerp and the vast majority is used to supply Rotterdam's demand, which as seen in figures 6.6, 6.7, and 6.8 are always much higher than the rest of the ports.

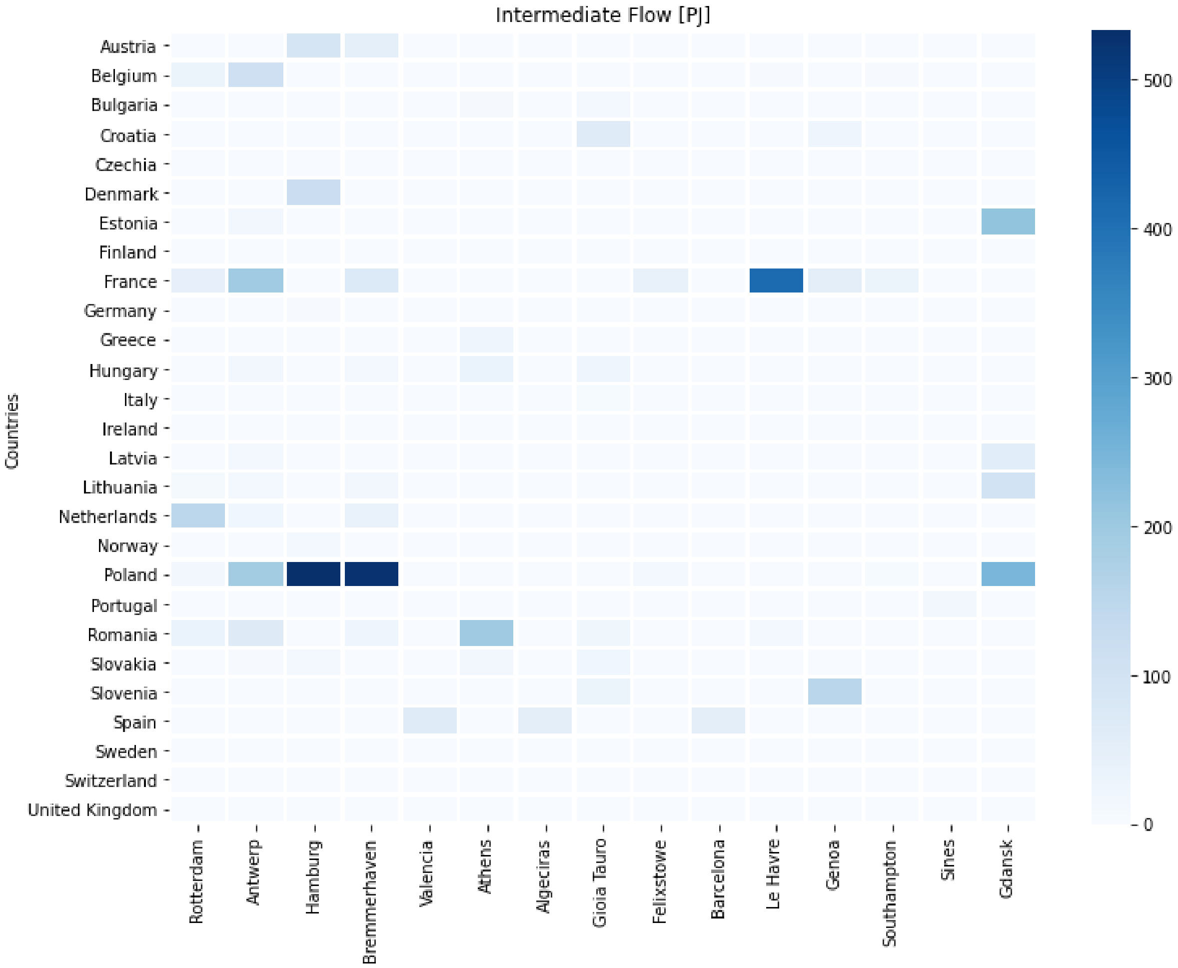


Figure 9.51: Heatmap of intermediate flows from country to ports.

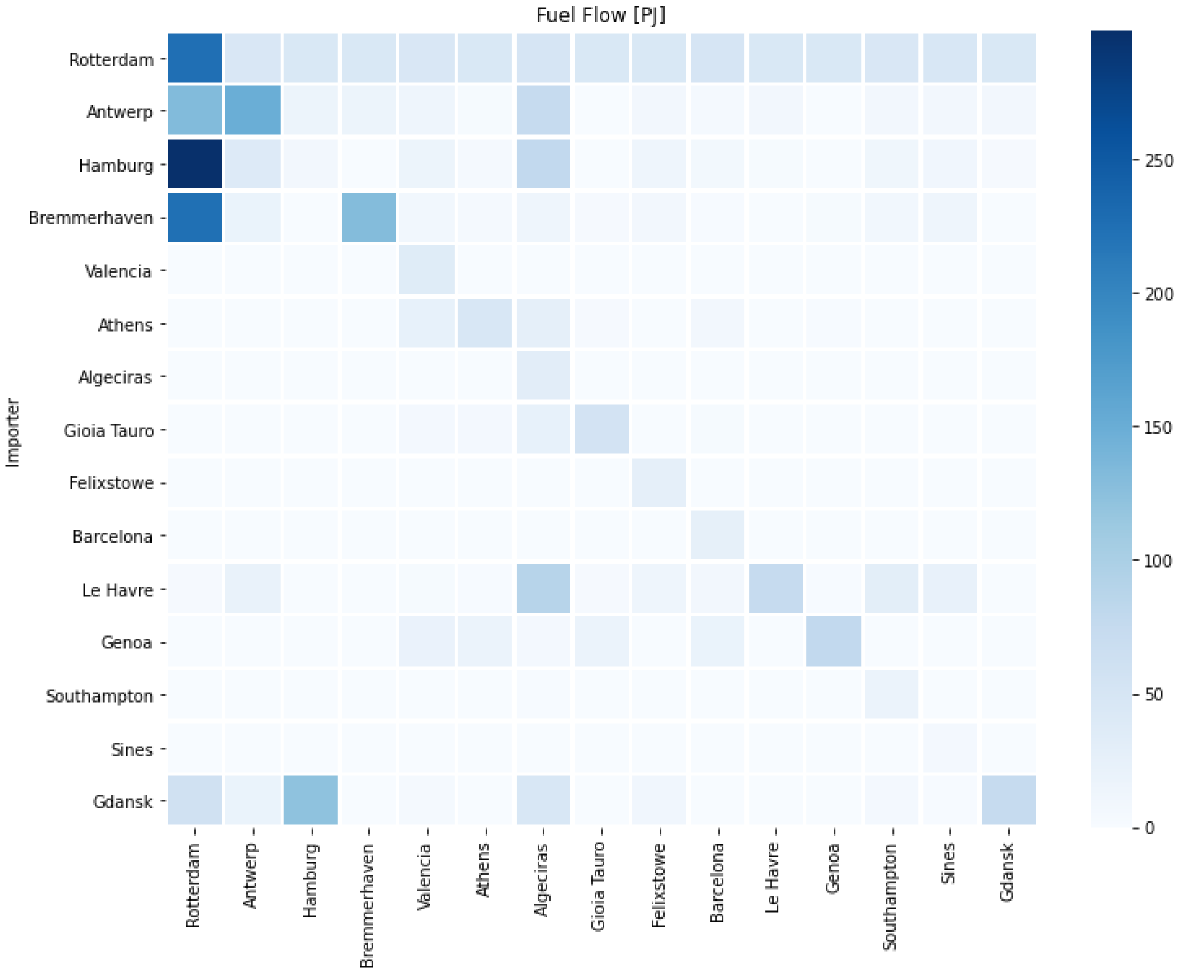


Figure 9.52: Heatmap of fuel flows from port to port.

10

Results & Discussion

In this chapter, the results from the optimization model, based on the runs, are presented and discussed. Further, the methods, strategy and shortcomings are reflected upon.

10.1. Reflection on Research Approach

The goal of this thesis was to assess the suitability/potential of biomass for the production of three fuels for short-to-medium term adoption within the maritime industry in Europe. The first couple of chapters in this report outlined some of the biggest concerns industry stakeholders shared relating to biofuels. One of the biggest considerations relating to the uptake of these fuels was their potential supply, not only in terms of biomass availability, but also production potential as well as the resultant emissions and costs. Additionally, it was unknown what the demand in future cases would lookk like (in terms of total energy and distribution) and which policies would bear more weight in their adoption.

To develop responses to these questions, it was decided to create a simulation model that outputted a response to these questions as variables. The approach of this thesis has been centered around developing a holistic system that outlines the process of bio-fuel production on various scales, modelling the system through a series of linear equations and solving to optimality. After performing a comprehensive literature study, it was determined that a useful method of doing so was to formulate a transshipment problem through the use of a Mixed Integer Linear Programming model. The MILP model was connected to external excel databases to load in data, a GIS modelling software was integrated to visualize the results, and the model was coupled with a GUROBI solver to make use of the simplex method in the optimization. The solution method proved to provide the desired outputs.

Using past literature and various handbooks on biomass supply chain modelling, the most important components were identified and incorporated into the modelling equations. The supply and demand, as well as a large amount of the parameters used to describe the model were found to be slightly uncertain (especially in future modelling) and dependant on various external factors. Most of the parameters were collected from the same or similar sources to maintain consistency. However, to overcome these fundamental uncertainties, several demand/supply cases were developed. On top of this, a sensitivity analysis was performed to measure the effect of certain assumptions and fixed variables. By doing so, it was possible to understand the effects of these on the results of the model. With this in consideration, the scenarios were run, each providing a particular insight into the model behavior and future conditions. After which, the results gained from all scenarios were compiled and analyzed, reaching further conclusions on a larger scale.

10.2. Research and Model Limitations

Although the model shows results comparable with those found in similar studies, from which useful insight can be deducted, models are always a simplified representation of reality due to modelling choices and assumptions. Throughout the development of this research, it has been possible to identify several limitations of the model and the assumptions that surround it. Some of these conditions have affected the model more than others. In this section, each impediment in the model is pointed out and explained in terms of its usefulness, threat to the model's validity and effect on the results.

Unaccounted Supply Chain Factors

In the Literature Review (chapter 3), six main operations were identified in the upstream and midstream segments of biomass supply chains from previous literature. The model proposed in this thesis accounts for only three of these operations, namely; collection, pre-treatment and conversion. As was already reasoned, the biomass production and harvesting are not relevant to second-generation biomass sources as these are not made specifically for the production of bio-fuels. However, the storage step is a useful component of any supply chain which was indeed overlooked in the modelling. Though the storage of biomass ultimately has effects on the routes (location), costs (price), and time (storage), the nature of the time-period in question made any time related optimizations unlikely (the time-steps would have to be discretized into time-periods of months/weeks/days instead of years). Incorporating storage would ultimately change the framework of the optimization from a strategic to a tactical level problem, which would make the model more complex and dependent on extra variables. However more difficult, the choice of avoiding storage has effects on the final outputs. For one, it can be said that the total costs are an underestimation. Depending on whether on-site storage or intermediate storage locations (between source and refinery) is assumed, total costs could see and increase of 10-20% (also due to added transportation/loading and biomass degradation) [108]. Further, depending on the processing times and storage costs of different biomass types, certain ones could be more profitable than others, resulting in a change in optimal fuel. The emissions most likely wouldn't suffer a large change as the processing would still account for over 90% of the emissions.

On top of the storage, another factor that was not incorporated into the model were alternative modes of transport, in specific, rail and barge. A paper by Mahmudi and Flynn found that transshipment, or the transport through several modes becomes economic when the transport distance reaches a certain value (for a certain biomass) [109]. The main reason why this was not incorporated was due to a lack of train routes and API software to incorporate into the model. In the case of this study and according to the paper, transshipment and the incorporation of rail into the model would have probably reduced both costs and emissions. Especially for the transport of long-distance biomass from eastern European countries. The addition of this, (though unlikely) could have resulted in the use of more wet biomass types as it would reduce the first and second transport leg costs/emissions. Similarly, a system of marine trade routes for the transport of biomass and intermediate product (on top of fuel transport), would have also resulted in alternate results. In particular, and based upon the system's preference for forestry residues, a network of barge transport from the northern economies (Sweden, Finland, Denmark, Norway, Estonia, Latvia, Lithuania) would have made forestry biomass from these sources much cheaper to transport thus more available. From the current model, it cannot be determined with certainty how much influence the transport has on the uptake of biomass from these countries. However, this is something that could be explored in future models.

Model Framework & Boundaries

The framework and system boundaries upon which the model was built were chosen in such a way to reduce the amount of uncertainty and external factors. In this sense, the modelling environment was less chaotic and complex, but on the other hand it reduced the amount of accuracy and number/amount of outputs and focused the scope of the model to a few, fixed and previously determined variables. However, real systems are subject to various external factors, and even though it is impossible to account for all of these, they should at least be mentioned. To start, the import/export of biomass was not considered for any country outside those within scope. Although the whole purpose of the report was to look into the self-sufficient supply of fuel within the EU, certain dependencies and trade agreements would have effects on both the supply and the demand. A paper by the European Commission Knowledge Center for Bioeconomy outlined the dependence of the EU on external market players for the import/export of biomass [76]. Considerations on trade agreements between in-scope countries as well as external players could result in reduced or increased biomass supplies depending on the country.

Discretization of Parameters

In order to model the real-life system of entities, nodes, and parameter involved throughout the supply chain, only the most significant contributors were chosen. This was useful in reducing the amount of available paths within the model and consequently the runtime of each simulation. Apart from a reduction in accuracy due to framework resolution, this discretization had carry-over effects into the choices within the model as well.

To start, the geographical location of biomass was discretized at the national level, that is, at each country, which is similar to a NUTS 1 (Nomenclature of Territorial Units for Statistics) classification. It was assumed that the location and total potential of all biomass was located at a point within half of the radius of a respective country's equivalent circular area. In reality, biomass collection locations are dispersed throughout the country. A more accurate depiction of this could have been performed at a NUTS level 2 or even 3 (basic regions for the application of regional policies/small regions for specific diagnoses [110]). The result of this would have probably been a reduction of inland transportation, as more biomass would have been modelled at the outer-regions of countries, closer to ports and refineries (especially for land-locked countries).

Next, the system refineries and their locations were modelled as point clusters located at the ports themselves. Though a reasonable assumption for marine fuels (current locations of conventional oil refineries are largely located in coastal areas, see [8]), as can be seen from appendix B this is not the case for a large percentage of European bio-refineries. Many are located inland and are dispersed irregularly over the in-scope countries. Essentially, the discretization of refineries has had two main effects. For one, it has resulted in the increase of costs/emissions in all inland transport segments. By reducing the available refinery options to a select few locations, the total inland distances were increased causing cost and emission increases of up to 16% and 3.5%, respectively. And two, it resulted in the ommittance of certain feedstock categories. From the scenarios, it was shown that drier biomass was preferred in countries that were located far from refineries. Had the refineries been modelled as being in their actual locations, transport distances would have been significantly reduced for some countries resulting in the uptake of manure, sewage and biowaste.

Third, the number of in-scope ports considered was limited to fifteen in total. This consideration was done in order to reduce the uncertainty brought along by the (advanced) biofuel demand at each port. As chapter 6 showed, the demand of advanced biofuels was calculated as the RED II percentage of total enrgy consumption at each port. It was not possible to allocated the share of energy consumption for every European port, thus only the ports with the highest energy demands were chosen and approximated. Similar to inland transport, a higher discretization of ports could've led to shorter trade distances, and again, resulted in the uptake of biomass use and fuel production, specifically in the Scandinavian and north-eastern European economies.

Supply and Demand

Both the biomass supply and fuel demand were significant components of the report and held a heavy importance in the outputs and behavior of the model. Though not of an equal seriousness, the relationship between the two essentially determined the answer to some of the thesis' most important research objectives. It is therefore essential to point-out the assumptions made regarding these parameters.

To start, the relationship between the supply and demand was assumed to be static. That is, the supply was calculated in one way, and the demand in another, with no feedback bridge relating the two. In reality, the demand of goods and commodities such as biomass and fuels is strongly tied to the supply of those. The prices of feedstock are strongly affected by the demand for them. Though several scenarios were run to account for various supply/demand situations, the feedstock prices remained constant throughout all trials. The result of this assumption is a predisposition towards countries with lower costs despite respective supply. Further, the biomass costs used are all roadside costs based on the country average, which isn't perfectly accurate. If instead of average costs, a price range was available, the lower price range bounds of all countries would be used up first.

The biomass supply was calculated using a data-centered approach. The source of all the data was kept constant (for the most part) to ensure homogeneity. Each biomass potential was calculated in a separate way and considerations were taken to account for biomass that was technically unavailable. One aspect that was overlooked, especially for the collection of manure and agricultural residues, was the influence of farm size on availability and collectability.

The fuel demand was calculated based on total bunker energy consumption and the advanced biofuel energy share according to Annex IX of the RED II. Though a reasonable expectation of future demand, the RED II advanced fuel shares are targets, and not binding. Therefore the demand (most likely) will be lower, which will result in different solutions for the model. In the case where demand falls much lower than the predicted low/medium scenarios, the refinery constraints will not be such big issues and better results in terms of costs and emissions will probably be achieved.

Pre-treatment Phase

An important assumption was made with regards to all biomass kinds relating to the pretreatment phase. It was assumed that all feedstock types went through both a drying and a milling treatment before being transported to the conversion facility. This was done based on the fact that the refineries were assumed to be located at the coasts, so to not immediately disregard inland countries as suppliers based on their large transport distances. As can be seen from the results, the assumption served its purpose. However, this was achieved at the expense of something else. From figure 9.43 it was shown that a large part of the costs related to the pretreatment phase, which was largely based on a feedstock's moisture content. Though the pretreatment is useful in reducing costs and emissions over long distances, it is not always needed for fuel production. For various feedstock and conversion technologies, such as gasification and anaerobic digestion (which are suitable for all considered feedstocks), a pretreatment phase is not necessary for conversion. The raw biomass can be converted directly, although the fuel energy yield may be slightly different.

The result of this premise was an overall disinclination towards wet biomass sources, as these were most energy intense in the pre-treatment phase. This could have been a reason why there was not a significant uptake of the wet biomass types, especially sewage and biowaste. For future models, an option can be added to allow the system to decide whether to undergo or skip the pre-treatment phase for biomass which don't strictly require it for conversion. This, along with a more accurate placement of refineries, could result in very different model outcomes.

Shipping Fuels

Another factor that was not taken into consideration was the difference in costs and emissions pertaining to the shipping of the different fuels. The costs associated with shipping each fuel are not the same, LNG, for example, is more expensive to transport due to its cryogenic and compressed-state nature. Though neither the shipping costs nor emissions were very high, this could be a consideration to account for in future models, especially if the shipped distances are inter-continental.

Model Formulation

One of the main drawbacks in the way the model was formulated was the fact that the biomass outflows (from each country) were limited to one refinery per biomass type per year. In other words, it was not possible for a certain biomass from one country to travel to more than one refinery in any set year (in different amounts but complying with the availability). This of course, is not how this system would behave in reality. Modelling with continuous outflows (and theoretically infinite paths) would have been much harder, however, limiting the number of outflow paths to an integer value would have resulted in more realistic results, at the cost of longer computational times.

10.3. Interpretation of Results

The developed model was made to determine the optimal sourcing of biomass, the type, product flows and associated supply-chain costs and emissions. From the run scenarios, a lot of information could be gathered. Despite the shortcomings and modelling limitations of the report, the results gained from it can certainly provide insight into this subject, and specifically, the research questions formulated in chapter 2.

To start, one of the most apparent and clear outputs of the model in the various scenarios was the choice of biomass. Unmistakably, the model showed an overall inclination towards forestry residue biomass in every scenario. This choice was due to a balance of biomass physical properties, price and source location. The conversion and transportation advantages of this feedstock proved to outweigh the costs of the biomass and relative transport distance to conversion plants. It was also noted that the option to use forestry residues was more prevalent in scenarios with low or medium demands. When the demand was increased over a certain threshold (around 100 PJ per year, but also depending on the supply scenario), the model ran into an availability constraint with respect to forestry residues and opted for different feedstock choices. For options in which only one specific fuel was used, the choices differed. In the case of ethanol production, forestry residues still reigned supreme. For methanol, agricultural residues and livestock manure also made up a large quantity, and for LNG a significant portion of the feedstock was manure, on top of forestry residues.

The biomass suppliers were rather consistent throughout all run scenarios. The vast majority of biomass energy was supplied from Poland in the form of forestry residues. France was the runner up, followed by the Netherlands, which mainly supplied manure. Romania, Slovenia, Estonia and Spain all supplied a much lower quantity of biomass energy. The rest of the countries supplied biomass to a much lower extent. The countries with the lowest use included Czechia, Finland, Ireland, Sweden, Switzerland and the UK. Factors such as biomass supply, geographical location, proximity to refinery, fuel yield, feedstock prices and available trade routes were all determinants of a specific feedstock uptake. It was discovered that physical properties beared more weight in the selection than originally believed. On top of this, since the pretreatment of biomass was assumed to take place within the country of origin, and the pretreatment cost was largely a function of electricity cost and moisture content as well as LHV, countries with lower electricity costs were more suitable for sourcing. The preferred bio-types were those with low moisture contents and high lower heating values (such as wood), or those that were located relatively close to the refineries (small countries with ports, i.e. Netherlands, Belgium).

The trade routes were also very centered around a few strong ones, given that the biomass sources remained mostly constant. The routes between countries and ports were fairly straightforward, with a propensity towards the shortest path while still meeting refinery capacity constraints. Poland was a main exporter to the two German ports; Bremmerhaven and Hamburg, but also Antwerp and Gdansk. France mainly exported to Le Havre, but also Rotterdam and Antwerp when local capacities were used up. Insofar as the shipping routes, the majority of the product transport was centered around the northern European ports, specifically Rotterdam, Antwerp, Hamburg and Bremmerhaven. Though the capacities of Bremmerhaven and Hamburg were equal, Hamburg in general had more fuel outflows, since it is located more towards the east, where the majority of biomass originates from. Most of the biofuel produced in Rotterdam remained at Rotterdam to meet the energy demand quota there. In cases where the demand was low however, Rotterdam became a major exporter to all ports (depending on the scenario).

It was also noticed that in times when an energy deficit was necessary (the high demand cases, ethanol, LNG), the largest deficits would generally appear in the southern-Atlantic ports of Algeciras and Sines, as well as Barcelona. Algeciras by far had the largest deficits in terms of total energy. However, as a percentage of local demand, the deficits in Spain and Portugal were quite substantial. Moreover, a very large amount of fuel is shipped to these locations from the northern seaports. It is not the case that Spain and Portugal do not have the necessary supply of biomass, however, there is a strong absence of refining capabilities in those countries. Algeciras would greatly benefit from a larger installment of refineries, and could possibly become a large exporter to the Mediterranean ports if this was the case.

The choice of fuel production turned out to be largely dictated by the available processing capacities. There was a stronger inclination towards ethanol and methanol than LNG, mainly due to the installed capacities of both. Though the emission abatement range was comparably very tight (in terms of what was achievable) for all fuels and cases, the specific costs and emissions were not all that similar. It was found that emission abatement was almost entirely reliant on the conversion process, which was specific to the outputted product. Only 72.2 to 73.6% of an emission reduction (compared to the fossil fuel comparator; 94 kgCO_2/GJ) was achievable depending on the scenario. The case of ethanol proved to have the lowest unit energy emissions albeit at the cost of some of the highest unit energy costs. The case of methanol demonstrated both the highest unit emissions and costs, although it was the only fuel out of the three that was able to satisfy the energy demand completely. For this reason, the comparison between the fuels alone is not fully comparable, as with the other two fuels, the cheapest production paths were used up first, resulting in lower specific costs/emissions.

The average production costs ranged from 22-38 €/GJ and the average emissions from 25-37 kgCO_2/GJ. The costs were mainly distributed over the conversion, pretreatment and to a lesser extent, biomass costs and the second transport leg. The first transport leg costs, collection costs and the shipping costs were found to not be substantial in the whole analysis. To a certain extent, the emission distribution was found to be completely dominated by the conversion process. All other emission components combined didn't even account for 10% of the total emissions in any scenario.

10.3.1. Potentials

Looking back at the problem statement, it was explained that the potential of biofuels was to be explored on different levels, namely, theoretical, technical and economic levels. In the following paragraphs, each potential is looked into again and described with respect to what was gathered from the study.

Theoretical Potential

The theoretical potential is the overall maximum amount of in-scope biomass which can be considered theoretically available for biofuel production within fundamental bio-physical limits. The supply cases shown in chapter 5 outline the technical potentials in three situations. The theoretical potential is on average around 30% higher than what is displayed in the graphs. Given that the theoretical potential is based on the established production of these residues, which are all seemingly set to increase or remain stable over the next years. The theoretical potential of biomass for fuel production is well above the expected demand. Agriculture, forestry and manure show the highest theoretical potentials of all biomass due to their high availability's compared to the remaining two (biowaste and sewage). In terms of distribution, agricultural and forestry residues have the upper hand, due to their more homogeneous distribution throughout the member states. Although, it can be argued that manure has a high potential because there is a large amount located in central Europe, especially in France and Germany, where a large percentage of production capabilities are located.

Technical Potential

The technical potential is the fraction of the theoretical potential which is available under the techno-structural framework. Considerations such as harvesting techniques, infrastructure, accessibility, processing technologies, etc. are all taken into account. This shift from theoretical to technical potentials represents the largest change between any two potentials. The total amount of biomass energy available is greatly reduced in this bracket. For example, of the total amount of theoretical agricultural residues available, only about 50% are collectible and of those, 30% must be left on land due to soil organic carbon concerns. Add to this external competition and other uses, and what is left of the original potential is rapidly decreased. This is what is shown in the figures of section 5.6. The supplies are still notably higher than all demand cases. Even after the conversion yields have been taken into account (the lowest conversion yield for each biomass type, to create a lower bound), the potential is still enough to supply all demand cases. Even for the lowest supply case and the highest demand scenario, the demand over the entire period is only 46% of the supply.

One limitation that presents itself in this analysis is the biomass location and its proximity to refining facilities. At this point it becomes clear that feedstock sources that are located near a processing plant, specifically those with high capacities, hold an advantage in terms of transport than those that don't. It would be logical to say that countries such as Germany, The Netherlands, Belgium and France are well positioned in terms of supply and capacity. However, as the analysis demnstrated, there is more to it than technical constraints/strategical advantages. In the Economic Potential paragraph, it is demonstrated how economic considerations affect the results.

The real technical limitation however, is seen in the refinery capacities, which limits the total fuel production to about one exajoule over the entire period, or an average of 0.17 exajoules per year. This is first seen primarily for LNG in the ports outside of Rotterdam, Le Havre and Germany. Then ethanol, which although more distributed than bio-LNG, does not have the infrastructure of bio-methanol refineries and capacities. In this potential bracket, it becomes clearer that methanol and ethanol are better suited than LNG.

Economic Potential

After the biomass has been converted into fuel, the resulting product can be assessed on its economic potential. The economic potential is the share of the technical potential which meets the criteria of economic profitability within the given framework conditions. This is why the final product, or the fuel is considered in this step. Though this has not been looked into deeply in this report, something can still be said about it.

To start, it becomes noticeable that although certain countries and feedstocks have incredible technical potentials in their use, the system outputs that are different to these expectations. On top of strategic geographic location and refinery proximity, electricity costs and biomass costs are a strong determinant in the economic suitability. In other words, the overall price level of the country of feedstock origin becomes very important in the selection. On top of this, the price of the pretreatment process is an important contribution to the total costs. Therefore, biomass with lower moisture contents have higher economic potentials. An example of this is forestry residues in Poland. Though Germany has a similar technical potential of forestry residues as Poland, and is closer to large ports, the lower biomass and electricity cost offset the preference to Poland.

In terms of fuel prices, it is apparent from figures 8.9 and 9.42 that the final fuels produced in this report are nowhere near price competitive with traditional oil-based combustibles. However, as the validation of the model results showed, the prices attained for the considered fuels did fall within the range of similar studies. Whether this is enough of a reason to warrant their uptake and expand their use depends mainly on regulatory drivers. Looking back at section 6.1, four key drivers in biofuel markets were identified. The first, cost-saving, was already looked into. These fuels are not price-competitive with current alternatives. Further, the technological push/drive offered by these fuels is not enough to convince shipowners to use them and fuel companies to increase their production. There is no foreseeable near-future technological development in the use or production of these fuels that will be impactful enough to change their desirability. The only realistic option is for there to be a market-side pull of demand for green products. This market driver will most likely have to be enforced through regulatory drivers, environmental policies, and/or large EU-wide government subsidies.

Implementation Potential

The implementation potential is the fraction of the economic potential which can be implemented within a certain time-frame and under specific socio-political framework conditions, including institutional, economic and social constraints as well as policy incentives.

From what has been shown so far, it is not highly unlikely for these biofuels to reach markets within the specified time-frame. The supply and facilities exist to do so and on top of that, the fuels are of similar prices to current same biofuels. However, doing so would require an enormous amount of cooperation amongst the member stares. As specified earlier, there are multiple stakeholders in this industry, and though some could gradually adapt, a change like this could leave many players behind. What is needed are binding targets set below the current ambitions to allow the industry to adapt. Additionally, to curve the price of these fuels, the EU should set forth large subsidies or introduce carbon taxes to level the playing field for the different fuels. Infrastructure investments should be made in southern Europe, and supply channels should be reinforced along the north.

If this was to be achieved, however, the most important supply line would be between Poland and Rotterdam/Antwerp, supplying forestry residues and being converted into methanol, which is at a more mature phase than ethanol with regards to onboard combustion technologies. This would also entail setting up some sort of agreement with the ports to increase capacities for this fuel and nearby refineries, to ensure the production there.

10.4. Implications of Research

As was initially stated, the RED II directive off of which this report is largely based on (in terms of demand and energy targets) is not binding. Therefore, aside from feasibility studies such as the one done in this report, the EU could consider slowly tightening regulations and starting incentives to approach this reality. As was seen in the opening introduction of the report, private ship companies such as Maersk are already taking this step on their own. The uncertainty that lies ahead with respect to fuels and future regulations is causing shipowners and fuel companies alike to start exploring possible options. Such is the case with fuel companies like GoodFuels which are accelerating the energy transition through the use of biofuels, but also historically oil-based companies such as Shell. Recently, the oil giant made announcements of the opening of a biofuel plant in Rotterdam and plans on reducing the production of traditional fuels by 55% by 2030 [111]. So, while this decarbonisation plan is not yet legally binding for shippers, more specific and mandatory regulations are expected before 2030. Given that vessels have a useful economic life of 20-30 years, the target year of 2050 is only one ship lifetime away. Therefore, newbuilds should (for their own interest and the greater good) begin the production of more biofuel based ships or dual engine prebuilds. However, before charterers and shipyards begin adopting new-fuel ships, they need to have the assurance of a reliable, bunkering network across Europe. Bunkering facilities should be available within major ports (already or in the near future), even if it is through ship-to-ship (STS) or truck-to-ship (TTS). There is already a vast network of port infrastructure to accommodate for LNG bunkering across Europe. Methanol could be another promising option to expand upon based on availability and incumbent ship engine technologies.

Once a shipping vessel is fully built and operational, fuel usage takes up to 50% of the operational costs of running a ship, and is not uncommon to spend 4-5 million USD to refuel an empty large ship when fuel prices are high. From the marine fuel supply side, there are many bunker parties and many small ship owners, but only a small number of very large ship owners and refineries. Thus, the market determinants for bunker fuel prices lie with the few large companies operating large and very large liner ships, as they are the biggest fuel purchasers by volume [27]. The price of biofuels cannot yet match the price of oil, however, there is a benefit in the apparent marine market concentration (to a few players). It is easier to devise agreements with a few large players in the industry to set real and binding targets for fuel embracement and compliance.

Regardless, the push and adoption of new fuels is very tied in to the surrounding environment and external developments in technology and politics. It is very difficult to foresee all of the factors that will be necessary in this technological endeavor. One thing is certain however, legislating bodies, in particular the EU have the responsibility of making sure the future of maritime is set along this path. The rest of the stakeholders will have no choice but to adapt, as many are already doing.

10.5. Societal Relevance

Apart from the evident need for cleaner technologies and the push towards more environmentally friendly energy carriers, the benefits and significance of this study extend beyond these dimensions. For one, the results retrieved in this study will be of use to oil, fuel, chartering and ship-building companies. All of these stakeholders are and will be affected by the EU's future regulations. Research such as the one carried out in this study is useful to explore future possibilities in order to make recommendations under the face of uncertainty.

Moreover, in the social aspect, the production of biofuels has the ability to increase the standard of living.

By limiting pollution through CO_2 abatement and the use of fuels with less NO_x and SO_x, the health of residents where fuel is produced and consumed will be enhanced through increased air quality. Additionally, in the ECA zones where these fuels are used, there will be a less overall ecological impact.

On a macroeconomic level, the localized production of fuel from provincial bio-sources will lead to a higher export potential and a reduced regional trade balance (which in turn will positively affect the EU's GDP). In line with the Keynesian income multiplier theory, increased spending in a region will result in a proportionate increase in employment, income and profits in the regional sectors needed to supply the development. This in turn will lead to additional consumer demand which is captured by the induced multiplier effect. Ultimately, the result will be regional growth and increased demand. More important than this however, will be the increased security in the supply chain and the lowering of supply disruption risk. The recent coronavirus pandemic has demonstrated how interconnected and globalized the world is, and how fragile and catastrophic the disruption of those connections can be. By producing (clean) fuels locally and shortening the supply chain, a massive diversification of risk and an increased security of supply is attained. Moreover, for the EU's supply side, this also means increased productivity, enhanced competitiveness (on a global scale, due to novel technologies and products) and improved infrastructure. On the demand side, this will create wealth and income, and attract investment. These effects will trickle onto related industries, such as the chemical, transport and agricultural. These effects are well documented in literature, and models have been developed to quantify the socio-economic and environmental aspects of biomass and biofuels.

10.6. Academic and Scientific Relevance

It is fundamental to analyze how the current research can be a valuable contribution to the scientific and academic community and also to the maritime industry. Looking back at section 3, certain knowledge gaps were identified in the scientific literature. For one, it was found that few studies focused on the use of multiple feedstocks and end products considering the medium-to-long term supply particularities of the raw products. In this report, several demand scenarios were outlined for five total feedstocks over the course of 10 years. The results considered several factors, technical limitations and availability constraints. Though the analysis was not incredibly detailed, mainly due to the time discretization steps, various scenarios outlined possible biomass supply over the next years. This creates a range and margin for what can be expected and what is possible over the following years. Further, it was also previously identified that there weren't many studies that looked at biofuel supply chains over various countries and on a international level. This study looked at the international supply of fuels throughout several countries while taking the factors that differentiate each country into account. On top of this, the real factors outlining the specified area were considered and the solutions created a realistic picture of what is achievable in the EU. Further, the costs and emissions associated with these fuels were estimated and broken down, which will help make future selections and considerations.

11

Conclusion

The maritime industry and the shipping world in general are quickly changing. We find ourselves in the midst of a technological revolution and a societal evolution. No longer will the long-established, traditional fuel options of the past bear any weight in the clean prospects of the future. It is clear that oil companies, shipowners, and other industry stakeholders are slowly becoming aware of the impending change that is at hand. There is an urgent need for real solutions that are both realistic and attainable within the foreseeable future. Legislative bodies and marine organizations need to be on the same page with regards to current and future goals and objectives. The solutions proposed should be set ambitiously while also taking into consideration the interests and barriers of all industry stakeholders.

Biofuels have lowered lifecycle CO_2 emissions and very low sulfur levels compared to HFO and even VLSFO or ULSFO. As of today, they are one of the most, if not the most, suitable option for the large-scale abatement of CO_2 emissions in the industry. The current challenge with biofuels presents itself in terms of the supply and production of them. The shipping sector has little knowledge on handling and applying biofuels as part of their fuel supply. On top of this, it is unclear which fuels are most suitable for adoption in the short to medium term. Previous studies in relation to biofuels have mainly dealt with first-generation biomass centered around the production of bio-diesels.

The main goal of this report was to conceptualize a real life model through a simulation in order to gain insight on three specific new fuels and their production in the European Union. More specifically, it was intended to identify the most suitable feedstock options for the production of them by creating future demand scenarios. The main research question was formulated as:

Which are the most suited bio-raw materials and sources for the production of bio-LNG, bio-ethanol and bio-methanol in Europe for the first phase of the energy transition (2025-2030)?

To adequately answer the main research question, a series of sub research question were constructed in the second chapter. The answers/results from these sub research questions either formed the knowledge-base required to build upon, such as relevant frameworks and boundaries, or provided actual results. Together, the answers of the sub-research questions allow an answer to the main research question to be constructed. Consequently, prior to answering the main research question, the sub research questions will be briefly discussed and summarized in table 11.1.

Starting from the literature study, biofuel supply chains were researched and a strategy to model them was developed. From here, the supplies of the in-scope countries were assessed and quantified based on several constrains and availability factors. Next, the demand was explored and developed for multiple scenarios. Additionally, the adoption of biofuels throughout the fleet in the future was also explored. These inputs allowed a model to be developed which outputted the answers to the some of the main research questions. Finally, the model was tested through a sensitivity analysis and run for various scenarios, each contributing a particular insight into the research. These results were verified through several tests and comparisons, which proved for the most part that the simulation was real and free of mathematical or coding errors. Unfortunately, the

Sub-research Question	Answer
i) How can biofuel supply chains be accurately represented and modelled?	A number of methods have been developed to model biofuel supply chains. The most common approach consisits of forming a superstructure around the main chain segments and modelling~the system through a system of linear equations. In this paper, a MILP was developed to represent the four main segments of the system and solve them to optimality.
ii) What are the production capabilities (for biofuels) of each considered~country?	To answer this question, several sources (EU databases and public registries) were compiled to figure out the number of specific biorefineries in each in-scope country. Based on the average yearly fuel-specific plant capacities of refineries in Europe, the total potential output for each country was estimated. Considerations were also taken with regards to specific feedstock types and outputted product.
iii) What are the available and preferred trade routes inland and at sea for the transport of feedstock and fuel.	The answer to this question proved to be slightly lacking. Though barge and rail routes were not included, the inland transport of truck routes was considered. The inland routes were not as expected due to biomass properties and local refinery capacities. However, the preferred routes turned out to be a combination of distance, price level of country origin and nearby plant capacity. The shipping routes were mainly a factor of supply and demand relationships between ports.
iv) What is the bunker demand of European ports and how can this be used to model future demand?	The bunker demands were assed on the basis of past marine energy consumption in Europe and the relative port-specific share of the European market. The energy demand scenarios were largely based on the IMO's 2020 GHG study. Three demand scenarios ranging from low to high were developed to capture the inherent uncertainty regarding future modelling of fuel demand.
v) What are the costs involved in the production and distribution of the outlined biofuels?	The costs identified in the production and distribution of biofuels were classified into 5 main categories; feedstock purchase, collection, pretreatment,conversion and transportation. The bounds of total costs discovered in this analysis ranged from 22-38 /GJ. However, for the most realistic/probable supply and demand conditions, the average costs fluctuated around 24 /GJ.
vi) What are the lifecycle emissions of the considered biofuels?	The main emissions throughout the supply chain were distinguished to be a product of the collection, processing and transport segments. The specific emissions ranged from 25-37 /GJ and were mainly dependent on the fuel that was produced.

validation of the model did not prove to be super useful given that there are very few truly similar examples to compare this to.

It was found that on a theoretical level, the amount of biomass in Europe is sufficient to meet the foreseeable demand, in all cases. This is especially true of forestry and agricultural residue biomass. From a technical standpoint, there is still enough supply, especially in countries such as Poland, France, Germany and also Sweden and Finland. However, the production capabilities are centered around central and northern Europe, limiting the conversion and production to the northern countries and seaports. The economic potential however, limited the collection to cheaper countries such as Poland, Romania and Slovenia, but also strategically located countries such as France and the Netherlands. The production was centered around Germany, France, Poland, the Netherlands and Belgium due to proclivity to first optimize inland routes and then shipping routes.

Today, it is observed that ship owners, when facing investment decisions, tend to hedge their bets between available technologies. While this strategy minimizes the risk of choosing the wrong option, tends to come at a higher investment cost. This research sheds light on new technologies, and helps industry stakeholders make these tough decisions in spite of the involved uncertainty. Biofuels will remain more expensive than fossil fuels (with rare exceptions) unless the costs of mitigating climate change are going to be factored in the cost of fossil fuels, however, as was demonstrated, they are a realistic option. It is within the hands of legislators and companies to push for the switch. It won't be easy, but the rewards will pay off in the future.

11.1. Future recommendations

If this work is used as a basis for future knowledge and investigation, there are a few recommendations and improvements that can be made.

Firstly, all outlined model limitations should be considered and taken into account. If the same assumptions used in this report are used, the effects of them should be taken into account. It will be important for future research to understand some of the pitfalls and shortcomings before running into them inadvertently.

Second, since the research spanned over various countries, considerations in differentiation were made mainly relating to geographies, refinery infrastructures and costs in relation to each. In future analyses, it would be helpful to find out what other differences between nations are useful and incorporate them into the model for a more accurate depiction. This could relate to infrastructure (pipelines, railways), national projects, etc.

Further, since the size of the refineries and outputs were measured using public sources and estimated calculations, finding a more reliable source for refinery-specific outputs and costs would result in more accurate solutions. This coupled with more accurate refinery locations and deeper insight into competition with respect to refineries would be very beneficial in the model.

As discussed in the "Model Limitations" section, the pretreatment segment was extra for some production paths, and was not actually needed. Future models should allow for bridging between superstructure nodes that are not consecutive. In other words, in cases where possible and beneficial, the pre-treatment step should be jumped and the path should go directly to the succeeding segment. The same goes for any additional parts of the model that do not apply to all feedstocks/fuels/transports/etc.

With respect to the demand, more accurate models could be formed, and more realistic port-specific behaviors could be attained. This, for example, could be done by looking into the GHG emissions and bunkering statistics from reputable sources. Insight on port facilities for storage and bunkering of specific fuels would be useful.

Lastly, the biomass sources used in this study could be expanded. Since forestry residues were found to be the best-suited biomasss, a deeper look into the collection and supply-chain transparency with respect to wood could be helpful. Additionally, not all sources outlined in Annex IX of the RED II were considered. Of particular interest would be residues from industrial applications and algae, which although not at a commercial state currently, could change in the following years.

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A

Annex IX from RED II

Part A. Feedstocks for the production of biogas for transport and advanced biofuels, the contribution of which towards the minimum shares referred to in the first and fourth subparagraphs of Article 25(1) may be considered to be twice their energy content:

(a) Algae if cultivated on land in ponds or photobioreactors;

(b) Biomass fraction of mixed municipal waste, but not separated household waste subject to recycling targets under point (a) of Article 11(2) of Directive 2008/98/EC;

(c) Biowaste as defined in point (4) of Article 3 of Directive 2008/98/EC from private households subject to separate collection as defined in point (11) of Article 3 of that Directive;

(d) Biomass fraction of industrial waste not fit for use in the food or feed chain, including material from retail and wholesale and the agro-food and fish and aquaculture industry, and excluding feedstocks listed in part B of this Annex;

(e) Straw;

(f) Animal manure and sewage sludge;

(g) Palm oil mill effluent and empty palm fruit bunches;

(h) Tall oil pitch;

(i) Crude glycerine;

(j) Bagasse;

(k) Grape marcs and wine lees;

(l) Nut shells;

(m) Husks;

(n) Cobs cleaned of kernels of corn;

(o) Biomass fraction of wastes and residues from forestry and forest-based industries, namely, bark, branches, pre-commercial thinnings, leaves, needles, tree tops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil;

(p) Other non-food cellulosic material;

(q) Other ligno-cellulosic material except saw logs and veneer logs.

B

Bio-Refinery Distribution

The following are a series of snapshots of biorefiney locations across Europe. The website can be found at

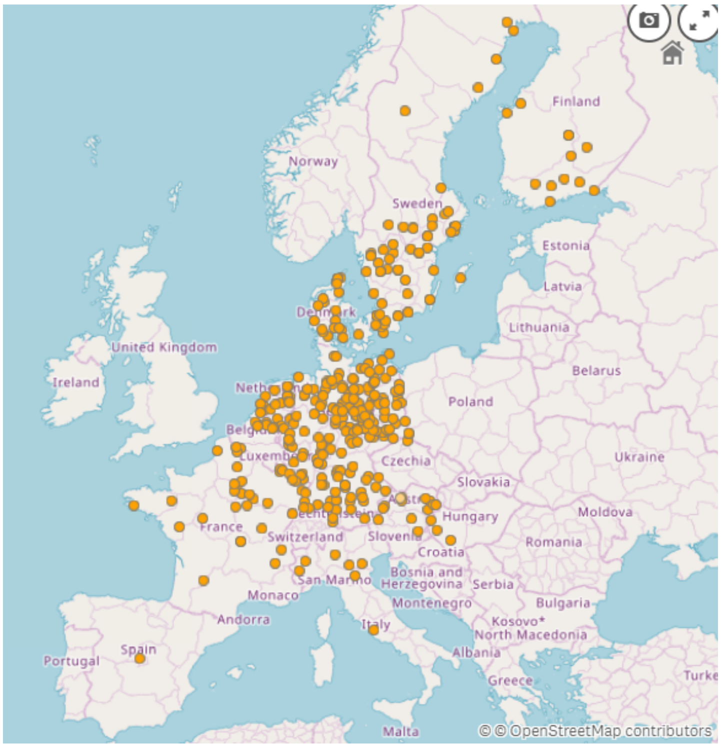

Figure B.1: Bio-methane refinery distribution [8].

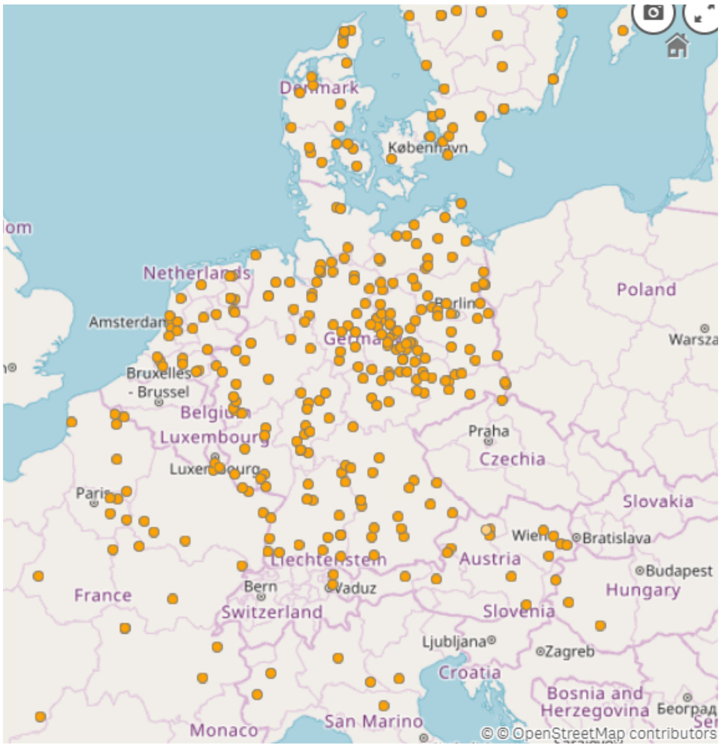

Figure B.2: Bio-methane refinery distribution (zoomed in) [8].

Figure B.3: Other biofuel refinery distribution [8].

	Biomethane		Biofuel		
	Existing	Pilot/demo	Existing	Pilot/demo	R&D
Austria	16	1	4	4	0
Belgium	0	0	9	3	2
Bulgaria	0	0	17	0	0
Croatia	0	0	1	0	0
Czechia	0	0	17	0	0
Denmark	22	0	10	5	0
Estonia	0	0	0	0	0
Finland	12	0	16	5	1
France	30	0	29	5	1
Germany	194	1	45	8	2
Greece	0	0	17	1	1
Hungary	2	0	7	0	0
Italy	7	0	18	2	1
Ireland	0	0	4	1	0
Latvia	0	0	0	0	0
Lithuania	0	0	0	0	0
Netherlands	27	0	16	5	2
Norway	0	0	0	0	0
Poland	0	0	16	1	0
Portugal	0	0	1	1	0
Romania	0	0	7	1	0
Slovakia	0	0	8	1	0
Slovenia	0	0	0	0	0
Spain	1	0	14	4	1
Sweden	63	0	12	4	0
Switzerland	0	0	0	0	0
United Kingdom	2	0	6	0	0

C

Feedstock Prices

	Forestry	Manure	Agriculture
Austria	4.17	1.65	6.82
Belgium	3.25	1.53	3.08
Bulgaria	3.03	0.74	1.71
Croatia	2.15	0.68	1.71
Czechia	4.67	0.73	2.72
Denmark	6.11	1.09	2.79
Estonia	1.93	0.72	1.65
Finland	6.02	1.68	2.79
France	3.54	1.83	1.54
Germany	5.57	1.57	3.54
Greece	2.67	0.76	2.25
Hungary	2.48	0.66	2.18
Italy	7.37	0.77	1.71
Ireland	5.55	0.00	0.99
Latvia	2.06	0.74	1.65
Lithuania	2.03	0.74	1.65
Netherlands	0.85	1.52	4.07
Norway	6.10	1.86	2.86
Poland	1.08	0.70	1.65
Portugal	5.00	0.71	1.43
Romania	0.18	0.71	1.71
Slovakia	1.84	0.73	2.95
Slovenia	1.42	0.76	1.71
Spain	3.83	0.59	1.43
Sweden	5.16	1.72	2.86
Switzerland	9.35	1.29	3.03
United Kingdom	5.13	1.80	2.97

Table C.1: Base feedstock prices in 2020 in €/GJ [15]. The feedstock prices of sewage and bio-waste are assumed to be zero.