Master's thesis

Biofuel utilisation in the Dutch maritime sector in a 2050 context

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Executive summary

The EU and subsequently the Netherlands have the goal of reducing GHG emissions from ships by 80% in 2050 compared to 2020 levels. To reach these goals the maritime sector looks to alternative marine fuels a solution, with biofuels prompted as one of the most promising solutions.

In the literature environmental impacts of biofuels have been researched extensively. The field of research towards biofuels is mainly focussed on LCA's of individual biofuels and techno-economic review of different biofuels. However, there is limited literature available concerning the environmental impacts and feedstock demands of large-scale biofuel utilisation on national basis. This study aims to help decrease this gap by investigating possible environmental impacts and feedstock demands of large-scale biofuel utilisation in a real-world context. The main objective of this exploratory study is to provide further insight in the environmental impacts resulting from large scale biofuel utilisation in a national context.

In the context of the EU emission reduction goals for the maritime sector by 2050, this study this study tries to answer the following question *"What are the environmental impacts of promising biomass-based biofuels used by the Dutch maritime sector by 2050?"* This study tries to quantify the environmental impacts of the feedstock production stage and the feedstock to fuel stage in biofuel production in a cradle-to gate format. Due to limitations these were studied separately in the same context, with the main focus on the feedstock production phase. Additionally, this study investigates the total energy and subsequent feedstock demands of biofuels in the context of the Netherlands.

The results of this study show a 296.1 PJ demand of energy from biofuels in the 2050 scenario, which is likely an underestimation due to the future growth of the shipping sector and limited shipping data available. To supply this demand, three biofuel technologies where selected, bioethanol, biomethanol and biodiesel. For each set of biofuels, a first generation and alternative generation biomass feedstock type was selected as supply for each biofuel. With use of different scenarios of biofuel mixes, the feedstocks required to supply the 2050 demand for each scenario. This resulted in feedstock demands for first generation feedstocks ranging from 5.2 Mt to 45.4 Mt of feedstocks per selected biofuel and different biofuel mix. The estimated demand of alternative feedstocks estimated was slightly lower, ranging from 1.7 Mt to 45.4 Mt between feedstocks per selected biofuel and respective scenario.

Through use of EEIOA, the environmental impacts of feedstocks of promising biomass-based biofuels used by the Dutch maritime sector by 2050 used for the production of the selected biofuel technologies were estimated for different scenarios of biofuel mixes. First generation feedstocks would require a larger increase in agricultural land area compared to alternative feedstocks. The total green water use of first-generation feedstocks for different biofuel mixes ranged from 118.45Gm3 to 206.15 Gm3 and the alternative generation amounting to 9.89 Gm3 to 10.59 Gm3. CO_2 emissions from feedstocks ranged from 28.70 Kt and 51.12 Kt for first generation feedstocks and between 2.89 Kt and 3.09 Kt for alternative generation feedstocks between the different biofuel mixes. N_2O emissions from feedstocks ranged from 25.00 t and 557.09 t for first generation feedstocks and between 23.29 t and 25.52 t for alternative generation feedstocks between different biofuel mixes.

The environmental impacts concerning the production of selected biofuels, scaled to future demand of selected biofuels for the Dutch maritime sector by 2050 amounted to the following. With all three biofuels supplying equal parts of the biofuel demand of energy in 2050, the production bioethanol from wheat straw is estimated to cause for 1.98 Mt CO_2-eq emissions. Biomethanol production from corn straw is estimated to cause 1.20 Mt CO_2 emissions and biodiesel production from UCO is estimated to cause 1.25 Mt CO_2-eq emissions in the same scenario. Other impact categories between the biofuel production phases themselves and the environmental impact categories could not be compared further due to lack in uniformity of results.

The main insights of this exploratory study are that large scale biofuel utilisation in the Dutch maritime sector, requires large quantities of additional biomass feedstock in the context of the Netherlands. The environmental impacts of feedstock production required for biofuel production should be considered debating biofuel production and can be mitigated by utilising alternative generation feedstocks, such as byproducts and wastes as feedstocks. In order to assess the environmental impacts of biofuels, there is need for comprehensive environmental analysis of wide arrays of feedstocks in combination with production methods concerning biofuel conversion. These should be performed in ideally the same research project or institution using identical assessment, standardisation and reporting, in order to make these comparable.

Contents

1. Introduction

Shipping in the maritime sector accounts for over 80% of trade globally (Foretich et al., 2021) and is estimated to be responsible for approximately 2.9% of global anthropogenic CO_2 emissions (Faber et al., 2021). The European Union has set the goal of reducing greenhouse gas (GHG) emissions of ships in the maritime sector by 80% in 2050 compared to 2020 levels (European Parlement, 2023). The Netherlands, an EU member state, is extensively involved in trade via shipping and the Dutch maritime cluster is responsible for 3.2% of the Netherlands GDP (Van den Bossche et al., 2022). This is illustrated through the port of Rotterdam located in the Netherlands, here the largest amount of fuel is taken on by ships, or bunkered, in the EU (Port of Rotterdam, n.d.). Reviewing possible solutions for climate neutral shipping in 2050.

The CO_2 emissions from shipping are largely a result of the consumption of fossil-based fuels in the maritime sector. In order to reduce GHG emissions from shipping, biofuels have been studied as an alternative fuel source for shipping and have been reported to reduce GHG emissions in the shipping industry by 25%-100% (Islam Rony et al., 2023). Alongside the potential of reducing emissions, biofuels are compatible with current power propulsion system of ships and maritime infrastructure (Kim et al., 2020). While biofuels do release CO_2 when these are combusted for energy utilisation, the CO_2 emitted during this process is considered as carbon neutral. The CO_2 released during combustion of biofuels is considered biogenic carbon. CO_2 that has been sequestered into the soil an taken up by the growth of feedstocks utilised for the production of biofuel. During combustion, the CO_2 sequestered is released again to the atmosphere, reaching a net zero in carbon emissions (Sebos, 2022). However, this does not include CO_2 emissions emitted during the cultivation of the feedstocks and the production of biofuels from these feedstocks (Jeswani et al., 2020).

While biofuels are seen as one of the most feasible alternative options to reduce GHG emissions from shipping (Serra & Francello, 2020), concerns about large scale biofuel utilisation have risen surrounding feedstock availability and environmental impacts of biofuel production (Roney et al., 2023). The literature regarding biofuel utilisation contains a large volume of life cycle assessments or LCA's and techno-economic assessments of biofuels (Al-Breiki & Bicer, 2021; Börjesson & Tufvesson, 2011; Deniz & Zincir, 2016; Kesieme et al., 2019; Tan et al., 2021 ; Zincir & Arslanoglu, 2024). However, there is limited literature available concerning the environmental impacts and feedstock demands of large-scale biofuel utilisation on national basis (Carvalho et al., 2021; Hansson et al., 2019; Perčić et al., 2021). Thus, this study aims to help decrease this gap by investigating possible environmental impacts and feedstock demands of large-scale biofuel utilisation in a real-world context. The main objective of this exploratory study is to provide further insight in the environmental impacts resulting from large scale biofuel utilisation in a national context. Due to the relevance of the earlier mentioned EU emission reduction goals for shipping and the Netherlands relevance in the maritime industry, these have been chosen as subjects for this study. Considering this, the question this study tries to answer is: *"What are the environmental impacts of promising biomass-based biofuels used by the Dutch maritime sector by 2050?"*

To answer the main research question and provide more context to the environmental impacts from large scale biofuel utilisation on a national basis, the following sub-research questions have been defined:

1. *What is the current energy demand of energy carriers used by the Dutch maritime sector for shipping?*

2. *What is the future demand of feedstocks as resource for biofuels in the Dutch maritime sector by 2050 for different scenarios of biofuel use?*
3. *Using EEIOA, what are the environmental impacts of the feedstocks used for the production of the selected biofuel technologies for different scenarios of biofuel use?*

4. *What are the environmental impacts concerning the production of selected biofuels, scaled to future demand of promising biofuels for the Dutch maritime sector by 2050?*

This study first presents the methods by which each of the sub-research questions and ultimately the main research question has been answered. This includes methods concerning quantifying the current and 2050 Dutch maritime demand for energy carriers, biofuel and feedstock selection with feedstock demand estimations. Additionally, methods used in the estimation of environmental impacts of selected feedstocks required for the production of biofuels using EEIOA and limited estimation of environmental impacts from biofuel production from feedstocks are included. Subsequently the results of this study are presented, including feedstock demands for biofuels in the context of the Dutch maritime sector for 2050 and environmental impacts of feedstocks in this context. Environmental impacts of biofuel production phase of feedstock to fuel are then presented followed by a comparison between environmental impacts from first and second generation feedstocks required for biofuel production. Subsequently in the discussion the results are further examined and put into context against literature, followed by the most notable limitations of this study. This culminates in the conclusion with mayor findings and takeaways of this study alongside future limitations.

1.1 Background

To study the environmental impacts of promising biomass-based biofuels used by the Dutch maritime sector by 2050, definition of core concepts is necessary.

Scenario for biofuel demand in the Dutch maritime sector for 2050

To assess the environmental impacts of the most promising biofuels in 2050, a probable scenario needs to be developed in order to put these environmental impacts into further context for the 2050-state of the Dutch maritime sectors fuel consumption. The Netherlands as an EU member state, has adopted the emission reduction goals for the maritime sector of the EU. Therefore, the scenario used as the 2050-state of the Dutch maritime sector is aligned with the EU reduction emissions goal for 2050. This states the following:

"*Maritime transport will also be included in the Emissions Trading System. MEPs want the maritime sector to cut greenhouse gas emissions from ships by 2% as of 2025, 14.5% as of 2035 and 80% as of 2050 compared to 2020 levels. The cuts should apply to ships over a gross tonnage of 5,000, which account for 90% of CO_2 emissions."* (European Parlement, 2023)

This is interpreted as an 80% GHG emission reduction by 2050 based on the current state. This is further simplified as replacing 80% of the current demand of energy carriers in the Dutch maritime sector with promising biofuels in 2050. This on the basis of the CO_2 emissions from biofuels upon combustion are biogenic and therefore carbon neutral. This results in a scenario in 2050 where 80% of the energy demand for energy carriers in the sector is supplied by biofuels. This scenario is referenced as the 2050 scenario throughout the study.

Biofuel feedstocks

Biofuels can be produced from a multitude of different biomass feedstocks. In this study, first generation biofuels are defined as biofuels that use biomass feedstocks that are mainly used for human consumption. Alternative biofuels are defined as biofuels that use biomass feedstocks not used for human consumption, i.e. second and third generation biofuels (ETIP Bioenergy, n.d.).

2. Methods

In order to answer the research question, the research design is formed according to the four sub-research questions. To answer the first sub-research question, the energy demand of energy carriers in the Dutch maritime sector for shipping is determined by sourcing the bunkered fuels in the Netherlands with a focus on freight carriers with a tonnage above 5000. Consequently, the promising biofuels are defined to enable further analysis towards feedstock demands and environmental impacts (Section 2.1). To estimate *"What is the future demand of feedstocks as resource for biofuels in the Dutch maritime sector by 2050 for different scenarios of biofuel use?"*, first feedstocks for the promising biofuels are selected. To enable further assessment of feedstock demands, scenarios for different biofuel mixes for the 2050 scenario are sourced from literature. These scenarios for biofuel mixes are further utilised throughout the study in the assessment of environmental impacts from biofuels. The earlier selected feedstocks required for biofuels are subsequently scaled according to the biofuel demand in the 2050 scenario using the estimated energy demand of the Dutch maritime sector and scenarios for biofuel mixes.

The main research question is directly assessed through operationalisation of the third and fourth sub-research questions. To answer the third sub-research question *"Using EEIOA, what are the environmental impacts of the feedstocks used for the production of the selected biofuel technologies for different scenarios of biofuel use?"* The environmental impacts of feedstocks are estimated for the Netherlands through use of environmentally extended impact output analysis or EEIOA. These impacts are scaled to the defined energy demand from biofuels in the 2050 scenario for different scenarios of biofuel mixes. To assess *"What are the environmental impacts concerning the production of selected biofuels, scaled to future demand of selected biofuels for the Dutch maritime sector by 2050?"* LCA data on biofuel production is researched from literature and scaled to the 2050 scenario and a comparative biofuel mix. This allows for further comparison between environmental impacts of the feedstocks required for the 2050 scenario.

2.1 Determining the energy demand of the Dutch maritime sector

In order to estimate "*What is the current energy demand of energy carriers used by the Dutch maritime sector for shipping?"* the energy demand, formula 1 is used. The specific energy density for each individual maritime fuel bunkered in PJ (Foretitch et al., 2021; Hsieh & Felby, 2017) is multiplied by the total amount of maritime fuel bunkered for each specific fuel of the set reference year. The resulting energy demand per fuel for the reference year is then summed to obtain the total energy demand of the Dutch maritime sector for in PJ for the reference year.

$$\mathbf{T}\mathrm{e} = \sum \mathbf{F}\mathrm{t} \times \mathbf{E}\mathrm{d} \quad (1)$$

Te = Total energy demand Dutch maritime sector for reference year[PJ]

Ft = Total maritime fuel bunkered of fuel type for reference year [kg]

Ed = The energy density of fuel type [PJ/kg]

2.2 Biofuel selection and biofuel mix scenarios

Biofuel selection

To assess the environmental impacts of promising biomass-based biofuels used by the Dutch maritime sector by 2050, promising biofuels have to be identified. Based on the following criteria, promising biofuels have been selected for this study. Technology Readiness Level (TRL), compatibility with current power and propulsion systems of ships and the current state of the maritime industries biofuel usage. These criteria are further specified down below. The criteria have been chosen to assess which biofuels are promising at the moment of writing this study, with the data available on their respective environmental impacts.

- Technology Readiness Level

Technologies selected in this paper must have a TRL of 9 according to the definition of the RVO, which defines that the product has to be technologically and commercially ready to enter the market (RVO, 2023).

- Compatibility with current power and propulsion systems of ships

The sustainable fuel alternatives examined in this study are also selected based on their compatibility with current power and propulsion systems of ships (Kesieme et al., 2019; Bilgili, 2023). Due to the high investment required for building ships and infrastructure required for ports to facilitate alternative maritime fuels (Wang & Wang, 2023).

- Current state of the maritime biofuel sector

In selecting the sustainable fuel alternatives examined in this study biofuels that are currently used in the maritime industry take preference due to the relevance of current development for the future.

Biofuel mix scenarios for energy demand

In order to answer the sub-research questions 2-4, scenarios of different biofuel mixes to supply the energy demand are necessary to calculate the environmental impacts of the feedstocks required for biofuel production a feedstock to fuel conversion, or production phase. Three scenarios for biofuel mixes are formulated for context. Two scenarios for biofuel mixes were defined through literature and based on projections of biofuel consumption in the maritime sector from literature to illustrate future demand. In addition, a comparative scenario was formulated to compare the environmental impacts and feedstock demands for different generation feedstocks.

2.3 Feedstock demand

To assess *"What is the future demand of feedstocks as resource for biofuels in the Dutch maritime sector by 2050 for different scenarios of biofuel use?"* For each selected biofuel a first generation and an alternative generation feedstock is selected to illustrate demands and environmental impacts from utilisation of different generation feedstocks. Selection of feedstocks for each of the represented biofuels is based on representation in literature and data availability in the FABIO database which is further described in 2.4.

Feedstock to fuel conversion

Next to a heterogeneity in feedstocks, biofuels can be produced using different production methods. These production methods have different energy conversion rates for the same biofuel category, as do the different feedstocks (Hsieh and Felby, 2017). For each selected biofuel and their respective feedstocks, the feedstock to biofuel ratio per unit of energy is sourced for the selected production method from life cycle assessments.

Determining feedstock demands

To assess the future demand of feedstocks as resource for biofuels in the Dutch maritime sector by 2050 the following strategy is used, the determined energy demand of energy carriers in the Dutch maritime sector was calculated for this replacement, for each scenario, biofuel and different feedstocks. Using the feedstock to biofuel ratios this was scaled to the feedstock demands in equation 2 below for each scenario, biofuel and feedstock.

$$\mathbf{F}\mathrm{d} = (\mathbf{E}\mathrm{d} \times \mathbf{E}\mathrm{b}) \times (\mathbf{E}\mathrm{n} \times \mathbf{B}\mathrm{f}) \tag{2}$$

Fd = Feedstock demand of energy carriers in 2050 from biofuels (Mt)

Ed = Energy demand of energy carriers in 2050 from biofuels (PJ)

Eb = share of energy demand of specific biofuel for specific scenario (no unit)

En = energy density of specific biofuel (MJ/t)

Bf = feedstock to biofuel ratio of specific biofuel and (first or alternative) feedstock (t)

2.4 Environmental impacts of feedstock resources of biofuels

To assess the environmental impacts of the feedstocks required for the production of the selected biofuels in a 2050 scenario, environmentally extended impact output analysis or EEIOA has been utilised. First the Food and Agriculture Biomass Input–Output database or FABIO is introduced, which provided the data required data to perform the EEIOA in this study. Then a general overview of EEIOA is presented followed by the specific application EEIOA in this study. Lastly the allocation of specific feedstocks is described in further detail.

Data

The database used for the EEIOA to assess the environmental impacts of the first-generation feedstocks and the alternative generation feedstocks for the selected biofuels, is FABIO. The FABIO, or Food and Agriculture Biomass Input–Output, database is an international dataset that consists of multi-regional physical supply-use and input-output tables that encapsulate agricultural activities. This is formatted in this way to be used in Input-Output Analysis and is based on Comtrade, FAOSTAT and other trade data that covers a wide array of 191 countries. This data includes a wide array of relevant commodities and processes. The version of the FABIO database used in this study is the FABIO v1.2 database, where 2020 has been used as reference year for this study (Bruckner et al., 2019). The environmental impacts categories selected from the environmental extensions in the FABIO database can be found in table 1 below. These impact categories were selected based on relevance and data availability in the FABIO database.

Impact category	**Unit**
Green water use	m3
Land use	hectares
Nitrous oxide	kg
Carbon dioxide	ton

Table 1 : Environmental extensions FABIO (Bruckner et al., 2019).

EEIOA

Environmentally extended impact output analysis or EEIOA is a method of environmental accounting based on linking economic production and consumption of regional and multiregional economies to environmental impacts (Kitzes, 2013). EEIOA is based on Input-Output Analysis or IOA, which captures the flows of goods and services in on or multiple regions and between industries, the EEIOA method extends Input-Output Analysis with environmental impacts (Miller and Blair, 2022). Below the general structure of an EEIOA is given in figure 1. The main elements of an EEIOA are as follows, the transaction matrix **Z** represents all the inter industry transactions and intermediate use of each product in the production of each product of regions. The final demand matrix **Y**, denotes the consumption of products by final use per region. Total output vector **x**, represents the total output of an industry and denotes the sum of intermediate and final use products per country. Value added **V**, represents the total value added for producing industries and regions. The environmental extensions or **F**, encompass the emissions and resource use resulting from the producing industries and regions. These are connected to the transactions between the industries and regions in the tables by means of environmental coefficients. These environmental coefficients are assigned to the transactions and represent the environmental impacts of each of these transactions between industries and regions. The structure and description of the elements is adapted from Miller and Blair (2022).

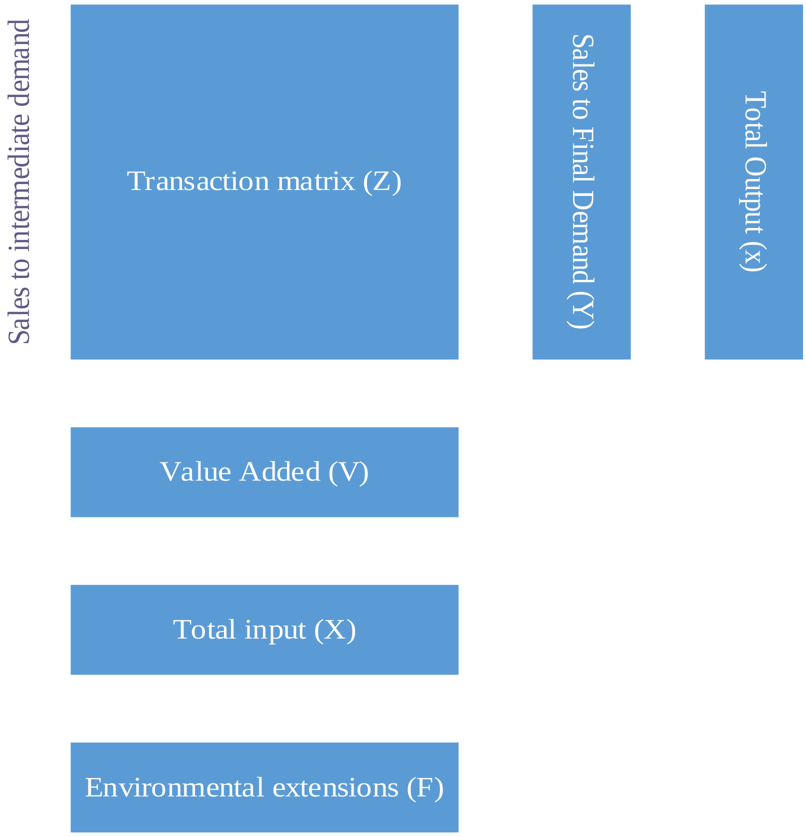


Figure 1: Input-Output framework general structure with environmental extensions (figure adapted from Brand-Correa et al., 2017)

To assess the environmental impacts of the products in FABIO that represent the feedstocks of the selected biofuels the following strategy is utilised. First the Leontief inverse is calculated. The Leontief inverse consists of coefficients that describe direct and indirect inputs between industries that are required per unit of final demand in the form of a matrix. The Leontief inverse is $(\mathbf{I} - \mathbf{A})^{-1}$, where **I** represents an identity matrix equal of **A**, and **A** represents the physical transactions between industries in the form of a matrix consisting of inter-industry coefficients. **A** is calculated from the **Z** matrix and the total output vector **x**, through equation 3 down below.

$$\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1} \tag{3}$$

Subsequently, the environmental impacts are calculated based on the consumption of the Netherlands in a multi-regional context. This environmental dimension of the EEIOA, is calculated using equation 4 below for the selected impact categories.

$$\mathbf{e} = \mathbf{f}\,(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} + \mathbf{F\_hh} \tag{4}$$

The environmental impacts or e are calculated by the formula above, for each impact category. Where **f** represents the direct environmental extensions in the form of an emission coefficient in emissions in kg or m^3/million dollars. **I** represents the identity matrix used for the calculations and **Y** represents the sales to final demand in million dollars and **F_hh** represents the direct environmental impacts per year in emission type, kg or m^3, per million dollars. The calculations 3 and 4 above are adapted from Miller and Blair (2022).

Sensitivity of EEIOA results and comparison between feedstocks

To assess the sensitivity of the total environmental impacts of feedstocks for each scenario to changes in environmental impacts and feedstock demands of individual biofuels, a sensitivity analysis was performed. Technically, the sensitivity analysis is performed changing in the environmental impacts and feedstock demands per unit of biofuel for each of the biofuels. Then a comparison was made of to what degree this impacts the total environmental impacts for each of the formulated scenarios.

After the initial stage of determining the environmental impacts of feedstocks, the environmental impacts of first generation and alternative generation feedstocks are compared. This provides more insight into possible differences in the environmental impacts between utilisation of first and alternative generation biofuels.

Allocation of environmental impacts for alternative generation feedstocks

In this study the decision was made to determine the environmental impacts of the alternative feedstocks categorised as byproducts based on value allocation of LCA studies. Certain alternative feedstocks categorised as waste products, are considered to have no environmental burden. The environmental impacts of the primary products of these byproducts were used as a starting point for the byproducts and weighted based on value through use of equation 5 below:

$$\mathbf{E}\text{b} = \frac{\mathbf{V}\text{b}}{\mathbf{V}\text{p}} \times \mathbf{F}\text{p} \qquad (5)$$

Eb = Environmental emissions byproduct

Vb = Value byproduct

Vp = Value primary product

Fp = Environmental emissions primary product

Reasoning behind this method these alternative feedstocks currently have value as a product, however the case of byproduct or waste can be disputed. This method is considered a general estimation, however since the goal of this study is to give a general estimation, within time constraints this was considered satisfactory.

2.5 Environmental impacts from the feedstock to fuel production phase

The strategy to estimate *What are the environmental impacts concerning the production of selected biofuels, scaled to future demand of promising biofuels for the Dutch maritime sector by 2050?* Is as follows. The production phase of the biofuels is defined as the feedstock to fuel phase, the phase where the biomass feedstocks are transformed into biofuel ready for use. To determine the environmental impacts from the production phase, existing life cycle assessment data, or LCA data, for each of the biofuels is researched by desk study. By use of the LCA data he environmental impacts of each of the selected biofuels per ton are isolated and scaled to the equivalent demand for the 2050 scenarios. The LCA data is selected on relevance towards the studied biofuel feedstocks, focussing on compatibility between feedstocks and production methods selected. In order to contrast the values above, this research is extended towards the fossil-based counterparts of the biofuels mentioned earlier in the environmental impacts from production phase section respectively.

3. Results

This section presents the results with a focus on answering the main research question through operationalisation of the sub-research questions. First in section 3.1, the scenarios for 2050 concerning biofuel mixes are presented, followed by the estimated feedstock requirements in section. Subsequently the environmental impacts of the feedstock production phase are presented in section 3.2, followed by a limited overview of the environmental impacts of the biofuel production phase in section 3.3. In section 3.4 a comparison of environmental impacts of between first and alternative generation feedstocks is provided.

3.1 Energy and feedstock demands

Energy demand

In order to estimate "*What is the current energy demand of energy carriers used by the Dutch maritime sector for shipping?"* energy carriers are defined as the maritime fuels bunkered within the Dutch maritime sector. The energy demand of energy carriers in the Dutch maritime sector for shipping, the Port of Rotterdam was selected to represent the Dutch maritime demand for energy carriers. The annual amount of fuel bunkered at the Port of Rotterdam was sourced from the reports of the Port of Rotterdam with 2023 as a reference year (Havenbedrijf Rotterdam N.V., 2023). When the total energy demand was determined per fuel, these were summed to give the total energy demand of the Rotterdam port in joules. The total energy demand expressed in bunkered fuels in 2023 came to approximately 370.1 PJ, what translates to biofuels supplying 296.1 PJ. The bunker sales report used as source can be found in the figure 7 in appendix A (Port of Rotterdam, 2024).

Towards 2050, the maritime sector is expected to grow compared to its currents state. The predicted growth in the 2018-2030 period of 2.3% and a 0.3% growth in the 2030-2050 period (DNV-GL, 2019). This expected growth is based on current projections, which are based on over 5000 tonnage mileage. Growth numbers corrected for 2023 assume a projected growth of 26.7% based on these projections. This growth will not be included in further analysis, but will be included in the discussion later on.

Biofuel selection

On the basis of the set criteria the biofuels bioethanol, biomethanol and biodiesel have been selected as promising biofuels for the Dutch maritime sector (Carvalho et al., 2021; Ellis & Tanneberger 2016; Kim et al., 2020; Korberg et al., 2021; Mohd Noor et al., 2018; Zincir & Arslanoglu, 2024). Below in table 2 feedstocks and production methods for each of the biofuels have been specified.

Biofuel	**Biomass feedstock**	**Process technology**	**Intermediary**	**Process technology (secondary)**
Bio-Ethanol	Sugar/ starch crops /Lignocellulosic biomass	Hydrolisis	Sugar	Fermentation
Bio-Methanol	Lignocellulosic biomass	Gasification	Syngas	Catalyzed synthesis
Biomass-derived diesel fuels	Oil crops/ Lignocellulosic biomass	Gasification/ pressing /extraction/pyrolysis/ Hydrothermal liquification	Bio-based oil product	Various

Tabel 2: Biofuels and production methods (Hsieh and Felby, 2017)

Feedstock selection

The biofuel feedstocks have been selected based on prominent feedstocks for each of the selected biofuels for which life cycle assessment studies are available. In addition, data availability concerning environmental impacts within the used FABIO database is included. Concerning the feedstocks for bioethanol and biomethanol, no specific product categories where available for these specific commodities in the FABIO database. However, wheat and maize where available, from which wheat straw and corn straw are byproducts. No direct alternative generation feedstock or feedstock in the form of a related byproduct could be found in the FABIO database, instead used cooking oil, or UCO, has been selected as the alternative feedstock for biodiesel. In accordance with this the following feedstocks have been selected, as shown in table 3 down below.

Generation	**Biofuel**	**Feedstock**	**FABIO item**	**FABIO item code**
First	Bioethanol	Sugar beets	Sugar beet	2537
First	Biodiesel	Rapeseed	Rape and Mustardseed	2558
Alternative	Bioethanol	Wheat straw	Wheat and products	2511
Alternative	Biomethanol	Corn straw	Maize and products	2514
Alternative	Biodiesel	Used Cooking Oil (UCO)	N/A (LCA-data)	N/A (LCA-data)

Tabel 3: Biofuel feedstocks per generation (Bruckner et al., 2019).

Scenarios for biofuel mixes

The energy demand from biofuels in the 2050 scenario is 296.1 PJ, or the biofuel demand in share of energy. To supply this demand, different scenarios for biofuel mixes have been defined. The scenarios for biofuel mixes of biofuels, bioethanol, biomethanol and biodiesel, have been defined in three different scenarios with the following characteristics.

1. Bio-methanol 44%, bio-ethanol 18%, biodiesels 18%
2. Bio-methanol 60%, biodiesel 16%, bio-ethanol 4%
3. Each biofuel 1/3 of total biofuel replacement (comparative)

In scenario 1 & 2 biomethanol represents most of the energy supply due to the fact that in recent projections methanol is identified as the most prominent biofuel for 2030 and 2050 in the maritime sector (Herzik, 2021). Scenario 3 is a comparative scenario, where all three biofuels are equally represented on an energy basis. This demand is supplied by each of the aforementioned biofuels in the scenarios described above, which translates to the energy burden of each biofuel in table 4 down below.

Scenario	**Bioethanol (%)**	**Biomethanol (%)**	**Biodiesel (%)**
S1	22.5	55	22.5
S2	5	75	20
S3	33.3	33.3	33.3

Table 4: Share of energy supply per biofuel to supply 80% emission reduction goals

Feedstock demands

Using the energy demand from biofuels in the 2050 of 296.1 PJ, *"What is the future demand of feedstocks as resource for biofuels in the Dutch maritime sector by 2050 for different scenarios of biofuel use?"* was calculated. The results are presented in table 5 for each of the feedstocks and biofuel mix scenario. Concerning the feedstock required per litre of biofuel and further energy contents used to calculate the feedstock requirements, appendix B can be consulted for further clarification.

Biofuel	**Feedstock**	**Scenario 1 feedstock requirements (Mt)**	**Scenario 2 feedstock requirements (Mt)**	**Scenario 3 feedstock requirements (Mt)**	**Main production methods**
Bioethanol	Sugar beets	28.9	6.4	42.9	Fermentation (Ayodele et al., 2020)
Biomethanol	Corn straw	33.3	45.4	20.2	Gasification and catalysed synthesis (Wang et al., 2024)
Biodiesel	Rapeseed	5.9	5.2	8.7	Pressing and transesterification (Malça et al., 2014)
Bioethanol	Wheat straw	12.6	2.8	18.7	Fermentation (Borrion et al., 2012)
Biomethanol	Corn straw	33.3	45.4	20.2	Gasification and catalysed synthesis (Wang et al., 2024)
Biodiesel	Used Cooking Oil (UCO)	1.9	1.7	2.9	Esterification and transesterification (Fonteinis et al., 2020)

Tabel 5: Feedstock requirements per scenario

The estimated demand of first generation feedstocks ranges from 5.2 Mt to 45.4 Mt of feedstocks per selected biofuel and different biofuel mix. The estimated demand of alternative feedstocks ranges from 1.7 Mt to 45.4 Mt and compared to the first generation feedstocks requires less total feedstock in terms of mass.

Corn straw, an alternative feedstock is included in the first generation feedstocks. This is due to a data limitation, however corn straw bears the complete environmental burden of the primary feedstock corn in the first generation scenario, not the value allocated environmental burden of the alternative generation. This is done to illustrate differences between a first generation methanol feedstock and an alternative generation feedstock.

3.2 Environmental impacts of feedstocks for biofuel production

Determining the environmental impacts of feedstocks

To assess *"Using EEIOA, what are the environmental impacts of the feedstocks used for the production of the selected biofuel technologies for different scenarios of biofuel use?"* through EEIOA, the environmental impacts of products that represent the feedstocks in Netherlands were assessed on a consumption basis by following the flows of mass through regions and sectors that ended up as products in the Netherlands. This resulted in a total emissions per product category as well as total amount of product consumed in tonnes of product. By dividing these an average of environmental impacts per ton of product in the Netherlands could be derived. The impacts per ton of feedstock are used later in the calculate the environmental impacts for the 2050 scenarios by scaling the environmental impacts by demand for the feedstock per corresponding biofuel in the scenarios for biofuel mixes.

Overview environmental impacts feedstocks per scenario

Using the calculated feedstock requirements in section 3.1, the environmental impacts for each of the feedstocks has been scaled according to the feedstock requirements per scenario. The impact categories presented are green water use, land use, CO_2 and N_2O as discussed in the methods. First an overview of all environmental impacts for each scenario and type of feedstock is given below in table 6.

Impact categories	**Green water use (Gm3)**	**Land use (million ha)**	**CO_2 (kt)**	**N_2O (10^1 t)**
Scenario 1(First generation)	172.30	47.20	44.14	452.61
Scenario 1 (Alternative generation)	10.59	3.15	3.09	26.26
Scenario 2 (First generation)	118.45	37.43	28.70	250.00
Scenario 2 (Alternative generation)	9.91	3.27	2.88	23.29
Scenario 3 (First generation)	206.15	53.26	51.12	557.09
Scenario 3 (Alternative generation)	9.89	2.71	2.89	25.52

Table 6: Table with total cumulative environmental impacts of all generation feedstocks

The total green water use of first generation feedstocks for different biofuel mixes ranges from 118.45Gm3 to 206.15 Gm3 and the alternative generation amounting to 9.89 Gm3 to 10.59 Gm3. CO_2 emissions from feedstocks ranges from 28.70 Kt and 51.12 Kt for first generation feedstocks and between 2.89 Kt and 3.09 Kt for alternative generation feedstocks between the different biofuel mixes. N_2O emissions from feedstocks ranges from 25.00 t and 557.09 t for first generation feedstocks and between 23.29 t and 25.52 t for alternative generation feedstocks between the different biofuel mixes. Examining these results, total environmental emissions for all scenarios using alternative generation feedstocks are approximately 77% and 95% lower for the different impact categories compared to the scenarios using first generation feedstocks. In 3.4 a full comparison between environmental impacts of first and alternative generation per utilised biofuel and feedstock is available. The environmental impacts of individual biofuels for each of the scenarios of biofuel mixes are described for first and alternative generation feedstocks below.

Environmental impacts first generation feedstocks

Below the environmental impacts are presented of the individual first generation feedstocks in the context of the different biofuels and scenarios. This is done in order to assess the environmental impacts between feedstocks required for biofuels in more detail. Below in figures 2 the cumulative environmental impacts of the first-generation feedstocks required for each impact category are presented separately per scenario, biofuel and impact category.

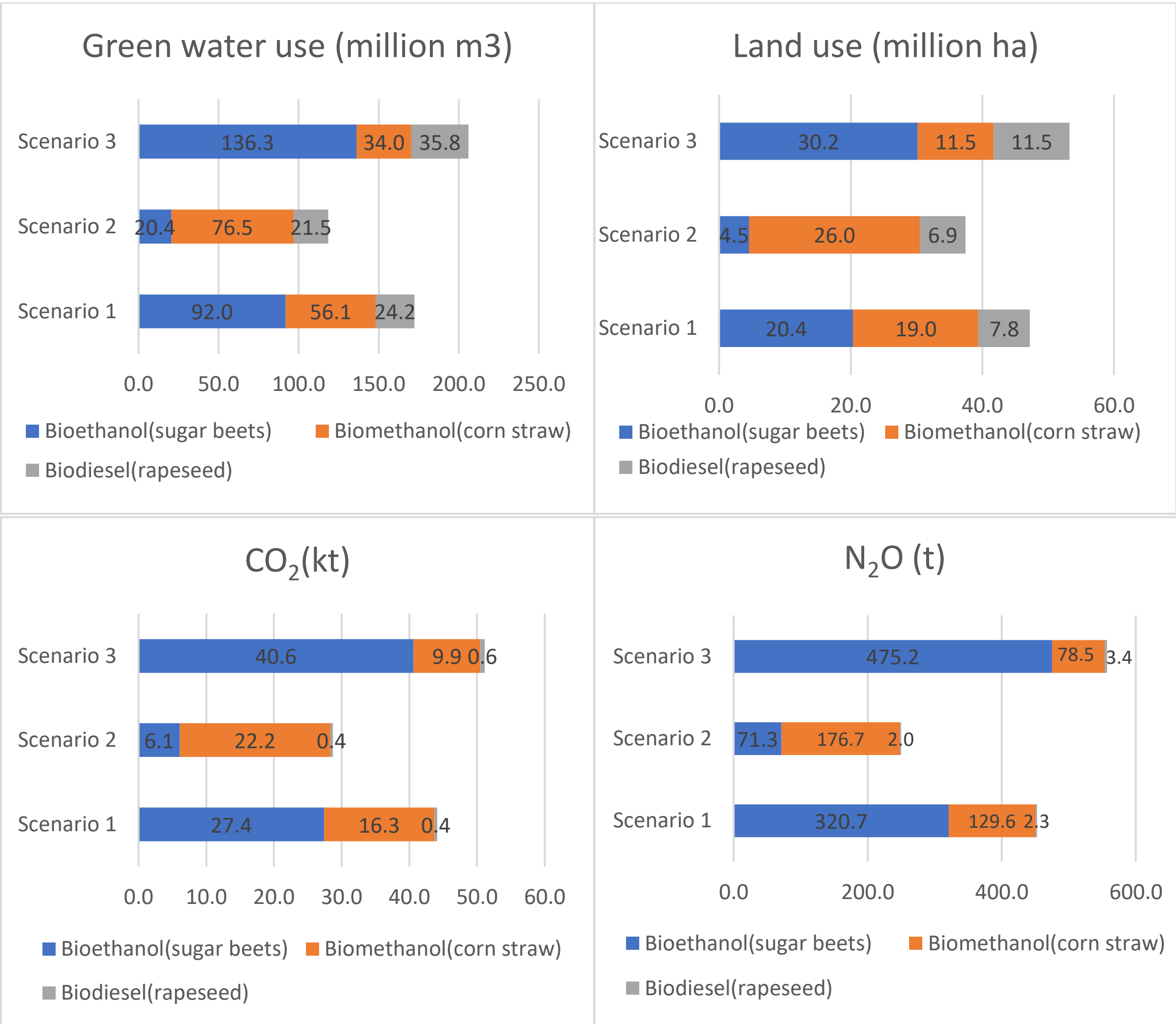


Figure 2: Environmental impacts of first generation feedstocks required for biofuel production in the 2050 scenario for different scenarios for biofuel mixes

Figure 2 shows that biomethanol feedstocks are responsible for the largest share of emissions in scenario 2, which is expected due to the relatively high use percentage of methanol in this scenario. However, in scenario 3, which is has all three biofuels share an equal energy burden, bioethanol is responsible for a comparatively larger share of the emissions. When examining figure 2, the production of biodiesel feedstock has the lowest overall emissions for each scenario across scenarios, excluding green water use and land use in scenario 3 compared to biomethanol feedstocks. Compared to bioethanol and biomethanol, biodiesel N_2O and CO_2 emissions are a fraction of the total emissions per scenario.

Due to the seemingly large differences in environmental impacts between the respective biofuels, i.e. feedstocks, a further comparison was performed. In figure 6, a spider diagram shows a comparison of the environmental impacts between the first-generation biofuels on a per MJ basis.

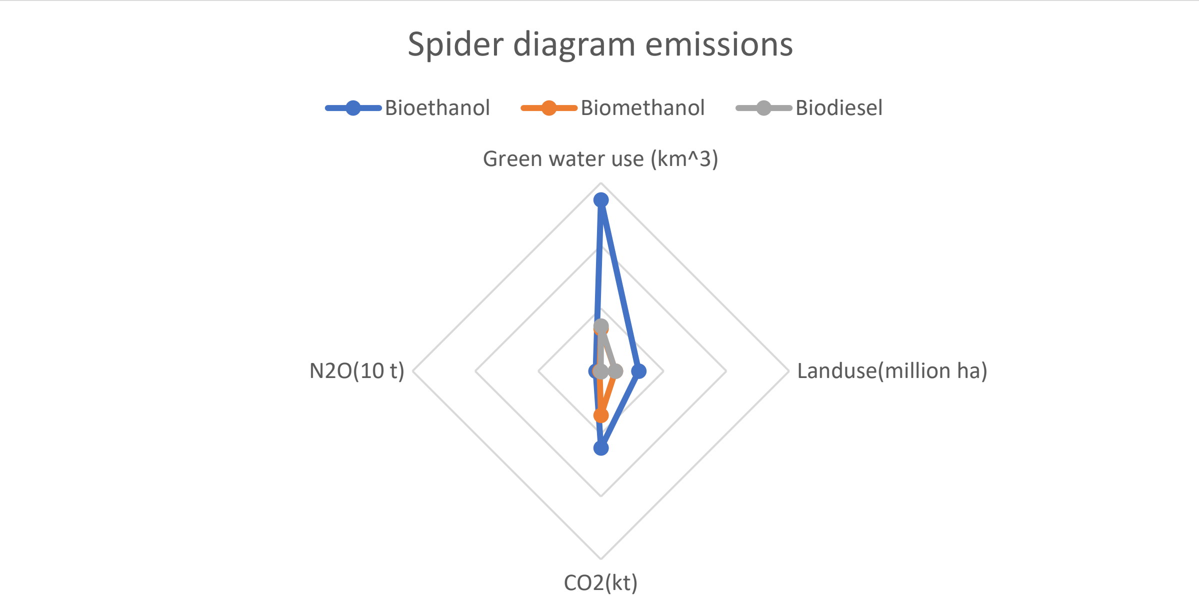


Figure 3: Comparison between environmental impacts on a per MJ basis between the first generation biofuels

In figure 3, the magnitude of the environmental impacts of the first generation feedstocks are compared for each impact category. Figure 3 above shows, that environmental impacts of feedstocks used for the production bioethanol are comparatively larger than for biodiesel and methanol feedstocks. However, the impacts of the biomethanol are still notably larger compared to the impacts of biodiesel for CO_2 and N_2O.

Environmental impacts alternative feedstocks

In this section the environmental impacts for each of the alternative generation feedstocks concerning bioethanol and biomethanol are presented in order to assess the environmental impacts between feedstocks required for biofuels in more detail. Because the biodiesel feedstock UCO is a waste, this has no environmental burden as a feedstock. Therefore, biodiesel is excluded in these results and the environmental impacts of this feedstock are considered to be equal to 0.

Below in figure 4 the cumulative environmental impacts of the alternative generation feedstocks for each impact category are presented separately per scenario, biofuel and impact category.

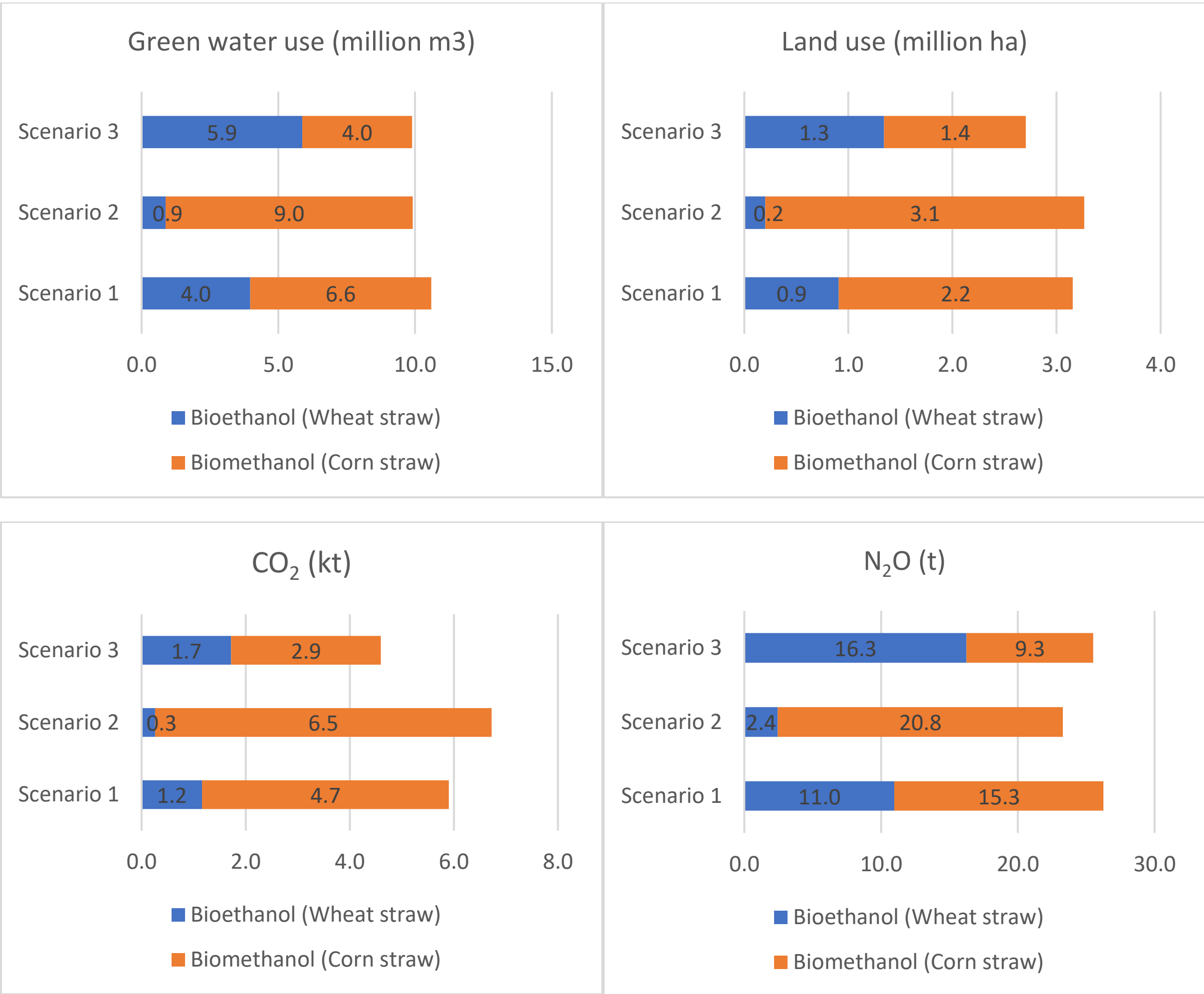


Figure 4: Environmental impacts of alternative generation feedstocks required for biofuel production in the 2050 scenario for different scenarios for biofuel mixes

When comparing all impact categories in figure 4 for each biofuel and scenario, corn straw for biomethanol production has the largest share of emissions in scenario 1&2. This is expected due to biomethanol supplying the largest share of energy demand in scenario 1 & 2. However, in the comparative scenario 3, wheat straw for bioethanol production is responsible for a larger share of total emissions concerning green water use and N_2O emissions.

Sensitivity of the environmental impacts

To assess the sensitivity of the total environmental impacts of feedstocks for each scenario to changes in environmental impacts and feedstock demands of individual biofuels, a sensitivity analysis was performed. The results of the sensitivity analysis show to what degree the total environmental impacts per scenario are influenced by fluctuations in the environmental impacts of individual feedstocks and feedstock demands. The sensitivity analysis assumed a 10% change, increase and decrease, in the environmental impacts of one of the feedstocks in each scenario. For each scenario and each feedstock this 10% change in emissions was performed separately for each feedstock and scenario. Subsequently the average change in total emissions was calculated per scenario for each feedstock. This also shows the sensitivity to change in the demand of feedstock required to produce an unit of biofuel due to the linearity of equations. The results are shown in figure 5 below, in appendix C the entire detailed sensitivity analysis for each impact category can be found.

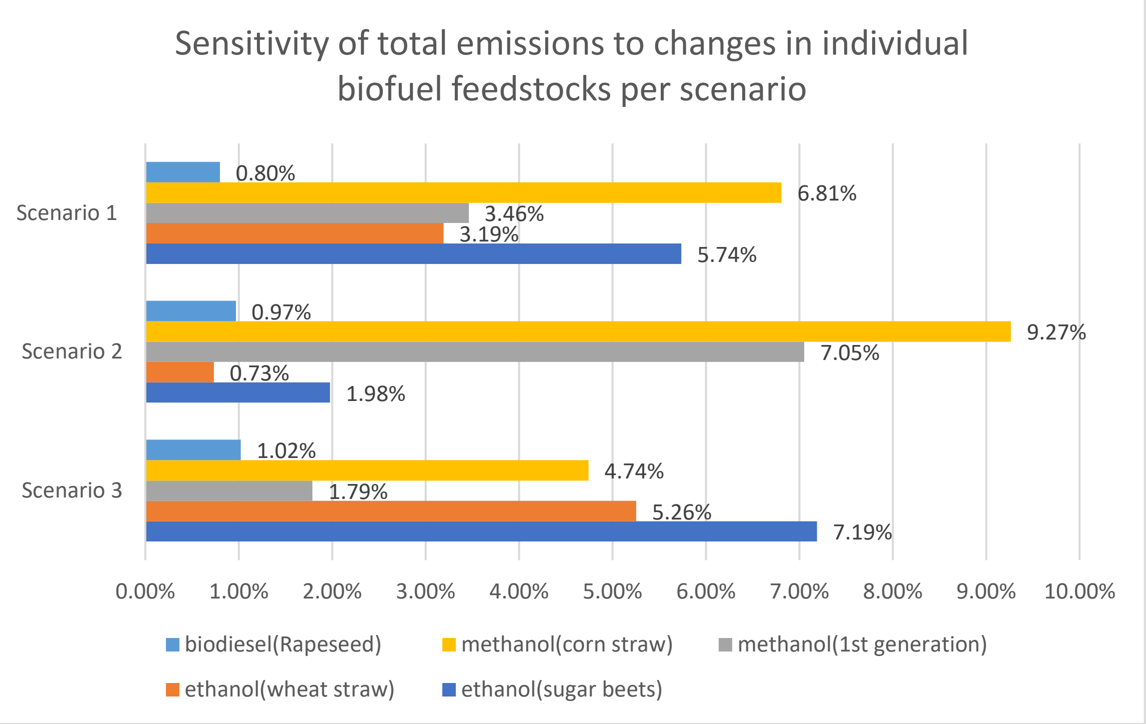


Figure 5: Sensitivity of total emissions to a 10% change in individual biofuels per scenario

The total emissions of scenario 3 are most sensitive to changes in emissions and feedstock requirements from first and second generation bioethanol feedstocks. Total emissions for all scenarios are comparatively not sensitive to changes in changes in first generation feedstocks from biodiesel. Which is most likely due to the comparatively low emission share of biodiesel across scenarios. Total emissions of scenario 2 are most sensitive to changes in both generations of methanol feedstock, probably a result of the 60% energy share of methanol. Total emissions from scenario 1 are most sensitive to changes in first and alternative generation feedstocks for bioethanol and methanol. Notably the sensitivity of total emissions to first generation bioethanol feedstocks in scenario 1 is 3.76% higher than scenario 2, while bioethanol energy demand is only 2% higher in scenario 1. Total emissions are is not susceptible to change in UCO as a feedstock, due to the fact that it has no environmental burden.

3.3 Environmental impacts production phases

In order to assess *“What are the environmental impacts concerning the production of selected biofuels scaled to future demand of selected biofuels for the Dutch maritime sector by 2050?”* life cycle assessment data on the production impacts of each of these biofuels has been used. For each biofuel one life cycle assessment study has been selected to represent the production impacts of these biofuels. Each representative life cycle assessment source used is described in detail per production method for further context below.

For each of the alternative generation biofuels, the same production methods used in the estimation of feedstock demands have been examined. This data has been scaled according to the energy demand and the respective biofuel demand in scenario 3. The impact categories for the feedstock production phase and the feedstock to fuel production phase are not uniform across studies, therefore they are not one on one comparable. To scale these values, the same feedstock demand per litre of biofuel used as in determining feedstock demands and the environmental impacts of the feedstocks required for the biofuel demands.

Specific LCA data concerning the production phases of the first generation feedstocks where not fully available and therefore not included. While the preference was to present multiple LCA studies for each fuel type and feedstock in order to be able to compare and assess the variability in these methods, due to lack of specific data concerning isolated production phases one study has been used per alternative feedstock.

Bioethanol – wheat straw

The LCA data selected concerning the feedstock to fuel phase or production phase of bioethanol, is Borrion et al. (2012). This study evaluates the entire life cycle of ethanol fuel, a specific part of this includes the environmental impacts of the conversion process of wheat straw to ethanol. This specific section is used to illustrate potential the environmental impacts of the feedstock to fuel cycle.

The first functional unit of the analysis in the study concerns the amount of fuel to drive 1 km distance by a small passenger car. However, the second functional unit the study employs is 1 kg of ethanol converted from wheats straw, which is evaluated in a well to gate context. This second functional unit is used in to illustrate the potential environmental impacts from the ethanol production from wheat straw.

This study has divided the feedstock conversion process of a generic wheat straw from a European region in different processes. The processes used in this study are feedstock handling, prehydrolysis, saccharification & fermentation, ethanol recovery and wastewater treatment, in that particular order. The LCA was modelled according to the generic life cycle assessment framework from ISO 14040 and 14044, using SimaPro 7.2 and the ReCiPe Midpoint methodology. The study used 18 impact categories, from which the most relevant impact categories are presented in the context of the presented feedstock emissions in section 3.2 and 3.4. Below in table 8, the results of the environmental impacts are scaled to the demand of bioethanol in scenario 3.

Impact Categories	**Global warming**	**Marine water eutrophication**	**Water depletion**	**Fossil fuel depletion**
Unit	Mt CO_2 eq	Ton N eq	10^3 m3	Kt oil eq
Environmental impacts scaled to scenario 3	1.98	631.73	129.10	3.65

Table 7: Environmental impacts from the bioethanol conversion process from wheat straw adapted from Borrion et al. (2012), and scaled to scenario, fulfilling a third of the energy demand for this scenario 3.

The article noted that CO_2 emissions in the bioethanol conversion phase mainly originate from the energy usage in the context of the used energy mix. Water depletion is relatively low when compared to green water usage from the feedstock stage, especially on this scale.

Biomethanol – corn straw

The LCA data selected concerning the feedstock to fuel phase or production phase of biomethanol, is Wang et al. (2024). This study evaluates the life cycle of bio-methanol as a fuel, using corn straw as a feedstock, in the context of the Shandong Province Weifang City in China.

This study evaluates the life cycle of bio-methanol as a fuel, using corn straw as a feedstock, in the context of the Shandong Province Weifang City in China. This study has defined this assessment in the following sections, straw growth, straw collection, and methanol production. The methanol production phase is used in to illustrate the potential environmental impacts from the methanol production from corn straw.

This study evaluates the environmental impacts of methanol production from corn straw using the GREET model, with the functional unit of 1 ton of methanol. The methanol production phase is divided in gasification, cleaning, gas conditioning, carbon removal, synthesis, and separation. The assessment includes a larger number of environmental impacts than presented in table 8 below, the most relevant impact categories are presented in the context of the feedstock emissions in section 3.2. In table 8, the results of the environmental impacts are scaled to the demand of biomethanol in scenario 3.

Environmental impacts scaled to scenario 3	**Energy consumption (104 MJ/t methanol)**	**CO (kt)**	**NOx (kt)**	**N_2O (ton)**	**CO_2 (Mt)**
Straw collection	206,717,672.70	23.00	41.00	224.33	8.29
Production stage	20,187,272.73	2.65	2.83	44.86	1.20

Table 8: Environmental impacts from the methanol conversion process from wheat straw adapted from Wang et al., (2024) and scaled to scenario 3, fulfilling a third of the energy demand for this scenario.

The straw collection stage is given as a reference. The study notes that CO_2 emissions are mainly a result of diesel and energy usage during collection for transport, and CO_2 emissions are mainly due to energy consumption during the conversion process.

Biodiesel – UCO

The LCA data selected concerning the feedstock to fuel phase or production phase of biodiesel, is from Foteinis et al., (2020). This study evaluates the environmental impacts of biodiesel production from used cooking oil, or UCO, in the context Greece.

This study evaluates the environmental impacts of biodiesel production from used cooking oil, or UCO, in the context Greece. The environmental impacts were assessed using the life cycle assessment methodology from ISO 14040:2006/DAmd 1 and ISO 14044:2006/DAmd 2 using SimaPro 8 with the ReCiPe Midpoint methodology. This study mainly divided the assessment in two phases, the UCO transport phase and the biodiesel plant conversion phase. The latter is used to illustrate the potential environmental impacts from the biodiesel production from UCO.

The functional unit of the study is defined as the production of 1 ton biodiesel from UCO. The biodiesel plant conversion consists of the following phases, pre-treatment/purification, acid-catalysed esterification and alkaline catalyst transesterification. The study included 18 impact categories, from which the most relevant impact categories are presented in context of the feedstock emissions in section 3.3. Below in table 9, the results of the environmental impacts are scaled to the demand of biodiesel in scenario 3.

Impact category	Climate change	Marine eutrophication	Water depletion	Fossil depletion
Unit	Mt CO_2 eq	Kt N eq	Million m3	Kt oil eq
Total	1.47	-3.48	-8.83	583.65
Transportation	0.22	0.04	1.23	78.21
Biodiesel plant	1.25	-3.91	-10.06	505.44

Table 9: Environmental impacts from the methanol conversion process from wheat straw adapted from Fonteinis et al., (2020) and scaled to scenario 3, fulfilling a third of the energy demand for this scenario.

The UCO collection stage is given because since this is not included in the UCO feedstock, since it has no environmental burden as a waste stream. Notable is that marine eutrophication and water depletion are negative values, the author however does not explain what causes this.

Fossil fuel-based fuels for the maritime sector

In order to compare the production impacts from the production of the biofuels earlier to the production impacts from currently utilised fossil based maritime energy carriers, results from and comparative LCA have been used from Zincir and Arslanoglu (2024). These results have been scaled equal to the individual energy demand in scenario 3 per biofuel, to make the results comparable. Only the most relevant impact categories have been scaled and present, table 10 does not present all categories from the study. Note that the biodiesel in this production phase uses soybeans as a feedstock. MDO, MGO and ULSFO are all prominent fossil-based fuels used in the maritime industry.

The goal of this study was assessing environmental damages during life cycle for the alternative fuel among which biogas, dimethyl ether, ethanol, liquefied natural gas, liquefied petroleum gas, methanol, ammonia, and biodiesel. This study had a functional unit of ton or equivalent volume of fuel and used SimaPro V9.0.0.49 and ReCiPe 2008 V1.09 for the assessment.

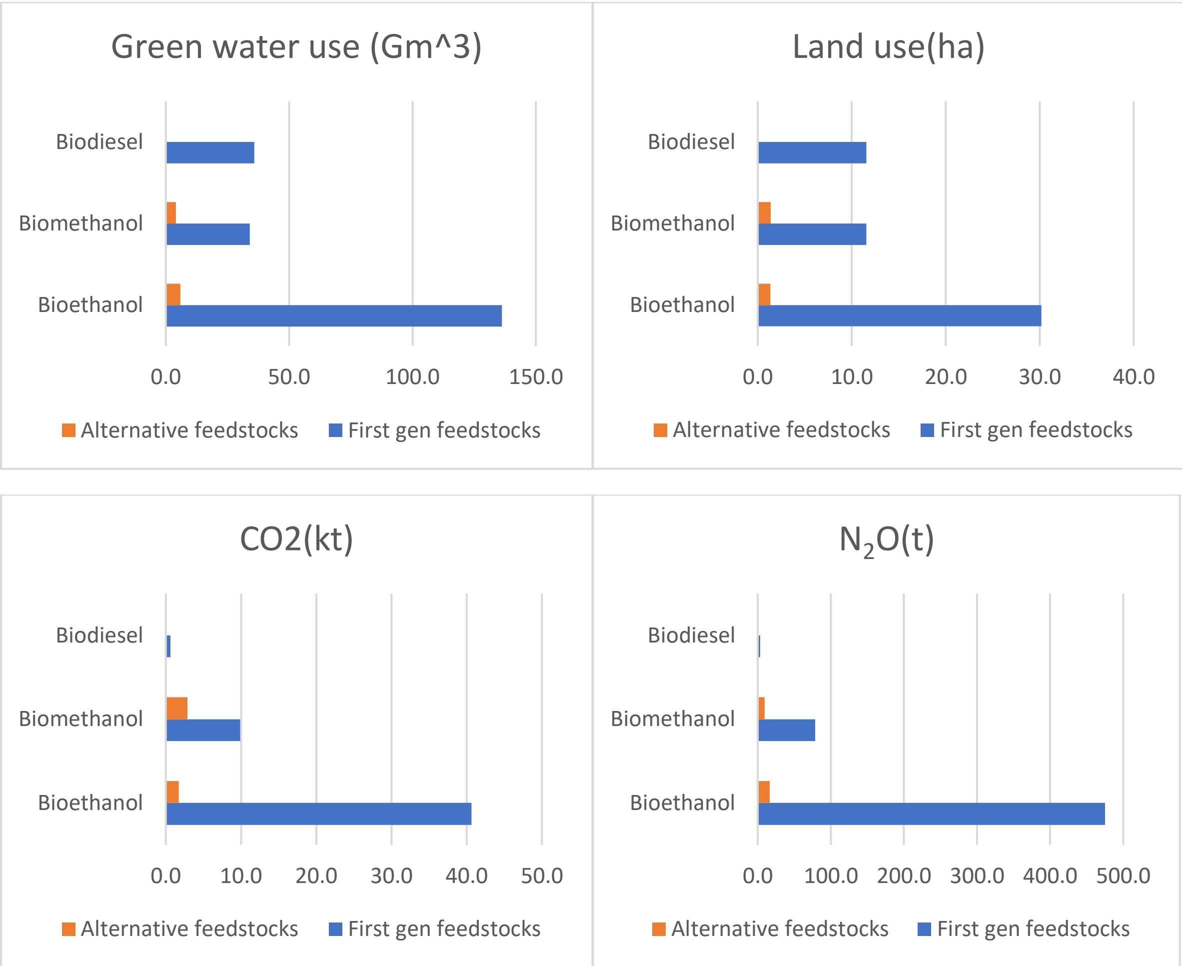
Fuel	CO_2(Mt)	CO(t)	NOX(t)	CH4(kt)	N_2O (t)
MDO	0.55	349.80	774.56	1124.35	7.50
MGO	0.52	349.80	774.56	1024.41	7.50
ULSFO	0.60	374.78	799.54	1224.30	7.50
Biodiesel	1.60	574.67	1024.41	2623.49	14.99

Table 10: Results from Zincir and Arslanoglu (2024) scaled each individually to a scenario 3 perspective, i.e. fulfilling a third of the energy demand for this scenario.

MDO, MGO and ULSFO fuels have lower CO_2 emissions from the production phase compared to biodiesel produced from soybeans. With CO_2 emissions from the production phase of biodiesel resulting in a 167% increase compared to ULSFO, a 191% increase compared to MDO and a 208% increase compared to MGO.

3.4 Comparison environmental impacts first vs. alternative generation feedstocks

In this section the environmental impacts of the first generation and alternative generation feedstocks for each of the biofuels are compared. The comparisons are shown for each impact category, per distinct biofuel and scenario below in figure 6. These present a comparison on the basis of scenario 3, since this allows for comparison on a per MJ basis due to the equal shares of energy in each of the biofuels in the scenario.



Figures 6: Environmental impacts of first generation vs. alternative generation feedstocks required for biofuel production in the 2050 scenario for different scenarios for biofuel mixes

When comparing alternative and first-generation feedstocks in figure 6, a drastic difference between emissions in all impact categories is observed. This is expected due to the reduced allocated environmental burdens of alternative feedstocks compared to first generation feedstocks. In all scenarios the alternative feedstocks are favourable on each impact category and respectively for each biofuel type separately.

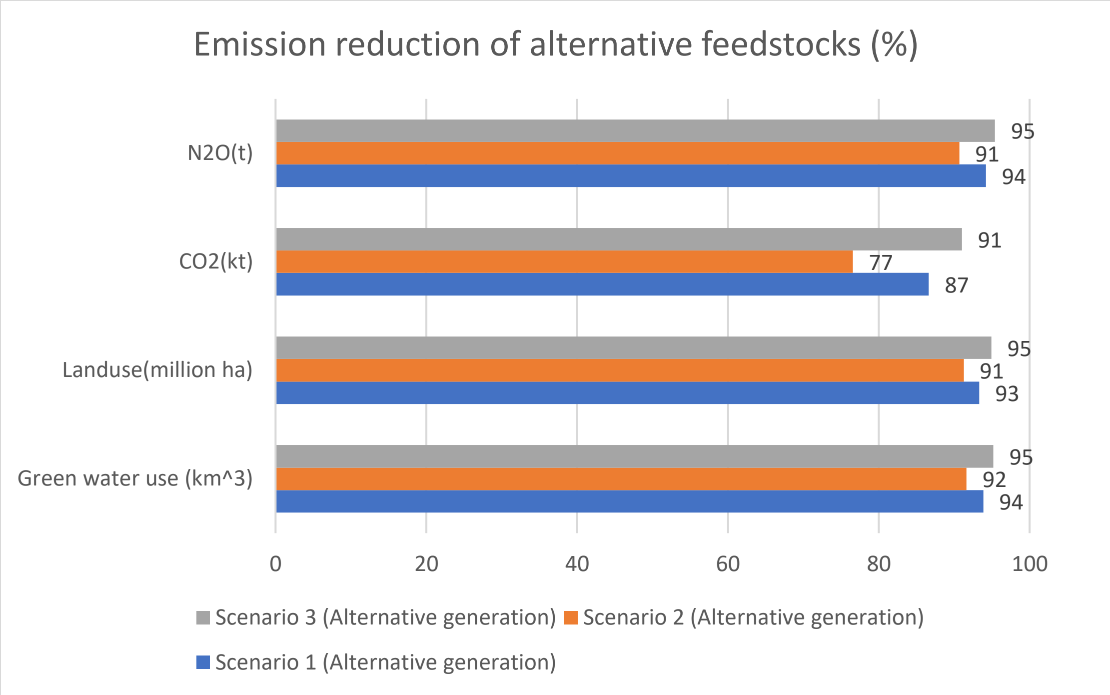


Figure 7: Comparative emissions of first generation vs second generation feedstocks for each scenario, on a percentage basis of the first generation feedstocks scenarios.

In figure 7 reduction of environmental impacts when utilizing alternative generation feedstocks compared to first generation feedstocks is presented. Figure 7 shows that on a scenario basis, alternative feedstocks reduce the emissions of scenario 3 by 91% to 95% for different impact categories. However, this is expected due to the fact that this scenario utilizes the most biodiesel and therefore the most UCO as feedstock. UCO is a waste and therefore has no environmental burdens across all impact categories, resulting the feedstock emissions for all impact categories of UCO being equal to 0. A similar trend can be found in scenario 1 & 2, which shows scenario 1 experiencing a relatively larger percentual reduction of 87% to 94% in emissions while utilizing a larger share of biodiesel. The 77% reduction in CO_2 emissions in scenario 2 is compared to the other scenarios and impact categories the lowest reduction of emissions. This could be a result of having the lowest biodiesel utilisation of all scenarios and CO_2 emissions having the lowest reduction rate of all impact categories.

4. Discussion and limitations

In this section the results will be further put into context and to what degree these findings answer the question, *"What are the environmental impacts of promising biomass-based biofuels used by the Dutch maritime sector by 2050?"* The earlier formulated sub-research questions were operationalised to answer this question, with sub research questions three and four explicitly answering the main research question. In the discussion the results of this study are reviewed, followed by the limitations.

4.1 Discussion

Energy demand

When addressing *"What is the current energy demand of energy carriers used by the Dutch maritime sector for shipping?"* The estimated energy demand came to approximately 370.1 PJ resulting in a 296.1 PJ demand of energy carriers in the form of biofuels, which was further used throughout the study as reference for 2050 demands. This was probably underestimated because this included exclusively the demand of the port of Rotterdam due to data limitations. Towards 2050, the maritime sector is expected to grow by 26.7% based on future projections. This, combined with the undervaluation of the energy demand of the Dutch maritime sector, indicates that the demand for biofuels and subsequent feedstock demands and environmental impacts could be larger than the results of this study suggest.

Feedstock requirements

The estimation of *"What is the future demand of feedstocks as resource for biofuels in the Dutch maritime sector by 2050 for different scenarios of biofuel use?"* showed a varying demand of feedstocks required for biofuels in the 2050 scenario in the context of the Netherlands. In the context of the Netherlands the amount of feedstock demanded is substantial. For example, the total corn production in the Netherlands for 2022 amounted to 8.4 Mt from 183.3 thousand hectares of land area in the Netherlands (CBS, 2023), which could deliver 9.4 Mt of byproducts based on the product to byproduct ratio (Wang et al., 2024). To exclusively supply feedstock required for biomethanol production from corn straw in scenario 3, agricultural land area of 393.5 thousand hectares would be required. First generation biofuels illustrate a similar demand. To supply the first-generation bioethanol in scenario 3, 28.9 Mt sugar beets is required. Based on current yields of the Dutch agricultural sector (CBS, 2023), approximately 353.6 thousand hectares of agricultural land are required. However, in 2015 the Netherlands total agricultural land area amounted to 22363 $km^{2,}$ or approximately 2236.3 thousand hectares (PBL, n.d.). This indicates that the demands for first and alternative generation feedstocks would likely exceed the Netherlands current agricultural capacity.

When comparing feedstock demands for respective biofuels, biodiesel seems most favourable on a mass basis. This is mainly due the comparatively high energy content of rapeseed and UCO, as well as the favourable conversion factors. When comparing first and alternative generation feedstocks, the alternative feedstocks require less total feedstock in terms of mass.

Environmental impacts of feedstocks

When addressing *"Using EEIOA, what are the environmental impacts of the feedstocks used for the production of the selected biofuel technologies for different scenarios of biofuel use?"* The following environmental impacts were found for each of the impact categories. Land use for first generation scenarios varied between 37.4 and 53.3 million hectares. Compared to the land area required in the Netherlands from the feedstock requirements above, this is magnitudes larger. Land use includes not only the arable land utilised, but extends to other additional changes necessary in infrastructure among others. Because the EEIOA methods accounts for and allocations emissions to the consumer, a lower average crop yields and increased land use in other countries could influence this land use due to Dutch imports. For example, Australia's average wheat yield over the past 5 years amounts to 2.4 t/ha (USDA, 2024), compared to the Netherlands 9.6 t/ha (CBS, 2023). However, in contrast with the feedstock demands from Dutch agriculture detailed above, land use results still seem disproportionally large.

The green water use of the feedstocks across different scenarios ranged from 118.5Gm3 to 206.15 Gm3 for first generation feedstocks and 9.9 Gm3 to 10.6 Gm3 for alternative generation feedstocks. Contextually, the total global green water footprint for rice production is 784 Gm3 per year (Chapagain & Hoekstra, 2011), indicating that the green water use for the different scenarios should be taken into account when utilising biofuels on this scale. When comparing all green water use footprints per ton of feedstock except UCO to literature, these exceed green water use found in the literature by more than a factor two except for sugar beets (Mekonnen & Hoekstra, 2011). For sugar beets our results seem to be more than ten times as large as found in the literature. No clear explanation is found concerning this finding, methods for assessing green water use concerning sugar beets are consistent with the methods for assessing green water use of the other feedstocks.

Concerning CO_2 and N_2O emissions, in context of the production phase emissions these seem relatively small for all scenarios and both generations of feedstocks compared to the CO_2 emissions from the production phase. It is difficult to compare these values to literature, because most specified emissions concerning feedstock production are deemed as negative in life cycle assessments of biofuels, because of carbon sequestration (Zincir and Arslanoglu, 2024).

Environmental impacts during the production (feedstock to fuel) phase

In answering *"What are the environmental impacts concerning the production of selected biofuels scaled to future demand of selected biofuels for the Dutch maritime sector by 2050?"* a limited number of comparable environmental impacts where found. When examining the environmental impacts of the conversion of feedstock to fuel for the alternative feedstocks, estimations of CO_2 or CO_2 eq emissions range from 1.20 Mt, to 1.98 Mt for scenario 3 emissions per biofuel. These emissions are mainly a result of the energy consumption from bioethanol and biomethanol conversion plants. However, while biodiesel conversion from UCO has comparable CO_2 emissions, the main cause of this is not specified in the source. The CO_2 emissions from production could be mitigated due to the use of energy that is largely decarbonised, such as photovoltaic and wind. When comparing these findings production emissions from prominent fossil-based fuels in the maritime sector, MDO, MGO and ULSFO, the fossil-based fuels have lower CO_2 emissions from the production process with CO_2 emissions ranging from 0.52 MT to 0.6 MT in a scenario 3 comparison. While due to data constraints it was not possible to perform an analysis of the environmental impacts from the production phases of the first generation feedstocks, comparison with conversion data from other feedstocks is still possible. Using soybeans as a feedstock in the biodiesel feedstock to fuel conversion process, the conversion from soybeans in a scenario 3 format resulted in 1.6 Mt of CO_2 emissions. This could be comparable to the CO_2 emissions from UCO conversion to biodiesel, that amounted to 1.25 Mt of CO_2-eq emissions. Concluding, the results of the production phases indicate that while a sustainable alternative to fossil fuels, when utilising biofuels on the scale of the 2050 scenario instead of the current fossil based maritime fuels, this could increase CO_2 and CO_2-eq emissions from feedstock to fuel, or production phase. This could be at least partially mitigated by using a renewable energy source.

4.2 Limitations

Scenario limitations

In defining the energy demand of the Dutch maritime sector there were limitations in understanding of what this precisely amounts to. By choosing the total bunkered fuels at the port of Rotterdam to represent the total amount of fuel consumed, there was awareness that this was limited. This excludes other smaller domestic fuel consumption, mainly from ships with a tonnage below 5000. However, the port of Rotterdam supplies fuel to many international ships. Additionally, the port of Rotterdam is one of the largest deliverers of maritime fuel in the EU, the delivered fuel likely exceeds amount of domestic demand. Coinciding with this is the fact that very little projections for the future biofuel mix used in the maritime are available, relying on a sole set of projections to set a biofuel mix. These limitations reduce the specificity of this study towards specific demands emissions of biofuel use in 2050.

Limitations on production data and feedstock inclusion

In this study a limited number of feedstocks and production methods are examined per biofuel. Emissions and biofuel yield per feedstock and production differ, which causes difference in total emissions and feedstocks. This is variability is increased due to differences in feedstock origins, which differ per country and year based on international trade. While the EEIOA method accounts for this, these fluctuations still differ per year between accounts. The choice of EEIOA to assess the environmental impacts of feedstocks based on domestic consumption, worked well in assessing the environmental impacts of multiple feedstocks but is less appropriate for assessing a large array of impacts using the FABIO database due to data gaps. This limited the number of environmental impacts that could be included, limiting the scope of the study.

While there is a larger body of LCA literature concerning the environmental impacts of certain biofuels, a limited amount of detail is available on the specific environmental impacts of specific production methods, and feedstock to fuel conversion, combined with a larger plethora of feedstocks. Especially LCA data concerning biomethanol production from biomass, excluding woody biomass, is very limited. As a result, it was not possible to include a first generation feedstock for biomethanol. Therefore, it was required to substitute with an alternative generation feedstock and accounting full environmental burden of its primary product, reducing representability of this analysis concerning first generation feedstocks. Furthermore, the comparison of results between LCA’s is difficult due to lack of harmonized standardisation and reporting between sources. In the assessing the environmental impacts of the production phases this rendered a problem because this resulted in comparison between different sets of impact categories that have different standards and definitions, which reduces the reliability of these results.

5. Conclusion

The main objective of this study is to provide further insight in the environmental impacts resulting from large scale biofuel utilisation in a national context. This study estimated feedstock requirements, environmental impacts from first and second generation feedstocks required for biofuel production using environmentally extended Input-Output analysis and environmental impacts from biofuel production from feedstocks in all context of the Dutch maritime sector in 2050. The main research question was *"What are the environmental impacts of promising biomass-based biofuels used by the Dutch maritime sector by 2050?"*

The results show that if the Dutch maritime sector would reduce its emissions from shipping by 80% through biofuel utilisation, biofuels would have to supply approximately 296.1 PJ of energy for shipping. Which is most likely an underestimation based on future growth. The feedstock required to produce the required biofuels ranged from 5.2 Mt to 45.4 Mt of first generation feedstocks and 1.7 Mt to 45.4 Mt between alternative generation feedstocks per selected biofuel and different biofuel mix. In the context of current Dutch agricultural production, probability of domestic production being able to supply the required feedstocks is low. First generation feedstocks require a larger amount feedstock and a larger increase in agricultural land area compared to alternative feedstocks.

The environmental impacts resulting from the production of the feedstocks required for the biofuel production in the 2050 scenario are as follows. The total green water use of first generation feedstocks for different biofuel mixes ranged from 118.45Gm3 to 206.15 Gm3 and the alternative generation amounting to 9.89 Gm3 to 10.59 Gm3. CO_2 emissions from feedstocks ranged from 28.70 Kt and 51.12 Kt for first generation feedstocks and between 2.89 Kt and 3.09 Kt for alternative generation feedstocks between the different biofuel mixes. N_2O emissions from feedstocks ranged from 25.00 t and 557.09 t for first generation feedstocks and between 23.29 t and 25.52 t for alternative generation feedstocks between the different biofuel mixes. Environmental impacts from the feedstock production and feedstock to biofuel conversion phases are not uniform, and could therefore not be presented as total values. With all three biofuels supplying equal parts of the biofuel demand of energy in 2050, the production bioethanol from wheat straw is estimated to cause for 1.98 Mt CO_2-eq emissions. Biomethanol production from corn straw is estimated to cause 1.20 Mt CO_2 emissions and biodiesel production from UCO is estimated to cause 1.25 Mt CO_2-eq emissions in the same scenario. The production of biofuels from feedstocks causes exponentially higher CO_2 or CO_2-eq emissions compared to the CO_2 emissions resulting from the production of feedstocks.

Takeaways

The main insights of this exploratory study are that large scale biofuel utilisation in the Dutch maritime sector, requires considerable quantities of additional biomass feedstock in the context of the Netherlands. The environmental impacts of feedstock production required for biofuel production should be considered when debating large-scale biofuel production and can be mitigated by utilising alternative generation feedstocks, such as byproducts and wastes as feedstocks. In order to assess the complete environmental impacts of biofuels, there is need for comprehensive environmental analysis of wide arrays of feedstocks in combination with production methods concerning biofuel conversion. These should be performed in ideally the same research project or institution using equal assessment, standardisation and reporting, in order to make these comparable.

Recommendations

While general this study does illustrate the magnitude of feedstock demands and environmental impacts for shifting a large sector such as the maritime sector in the Netherlands, the specificity is limited. Future research in this area would benefit from inclusion of a larger array of feedstocks and biofuels, with various production methods applicable concerning the feedstock to fuel conversion, since these can differ considerably. However order to assess the environmental impacts of biofuels more accurately, there is need for comprehensive environmental of wide arrays of feedstocks in combination with production methods concerning biofuel conversion. These should be performed in ideally the same study or otherwise using equal assessment, standardisation and reporting, in order to make these comparable. To make the research towards the practical use of biofuel feedstocks more robust, the following could be utilised. Studies towards the availability of byproducts and waste could be performed in combination with an assessment by what production methods and in which quantities these byproducts and wastes could yield different biofuels in a territory.

Reflecting on the use of EEIOA together with the FABIO database, these were found appropriate for assessing a consumption-based emissions profile for multiple feedstocks of different biofuels. The main limitation found concerned the data granularity of FABIO and the lack of LCA data concerning the specific production phases of the feedstock to fuel conversion that was deemed comparable. This caused the results of the study to be relatively indicative and less specific then intended.

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APPENDIX A

Port of Rotterdam

BUNKER SALES PORT OF ROTTERDAM **2021 - 2024**

Year	Quarter	ULSFO *in tonnes*	VLSFO *in tonnes*	HSFO *in tonnes*	MGO *in tonnes*	MDO *in tonnes*	Methanol *in tonnes*	LNG *in m³*	Fossil Subtotal *in tonnes*
2024	Q1	176,797	680,782	818,028	262,496	120,913	-	215,247	2,155,877
	Q2								
	Q3								
	Q4								
	Total	**176,797**	**680,782**	**818,028**	**262,496**	**120,913**	**-**	**215,247**	**2,155,877**
2023	Q1	221,254	984,034	809,871	258,137	210,236	-	86,088	2,522,272
	Q2	220,777	906,368	847,189	253,748	151,124	-	179,804	2,460,117
	Q3	186,803	810,553	790,195	234,690	144,452	-	204,418	2,258,682
	Q4	166,289	681,573	643,218	213,408	148,177	-	148,933	1,919,685
	Total	**795,123**	**3,382,528**	**3,090,472**	**959,984**	**653,989**	**-**	**619,243**	**9,160,756**
2022	Q1	213,075	930,481	707,312	286,996	209,529	-	102,579	2,393,553
	Q2	189,192	920,223	718,325	269,833	166,583	-	112,069	2,314,587
	Q3	205,451	986,058	835,812	298,085	161,186	500	133,352	2,547,101
	Q4	212,410	1,022,036	841,247	297,388	178,222	1,000	58,599	2,580,501
	Total	**820,128**	**3,858,798**	**3,102,697**	**1,152,301**	**715,520**	**1,500**	**406,599**	**9,835,742**
2021	Q1	201,054	978,145	620,752	250,570	174,361	-	139,489	2,287,652
	Q2	227,099	1,021,119	614,098	249,386	177,640	250	157,027	2,360,254
	Q3	199,188	1,051,017	694,133	258,797	183,987	-	212,719	2,482,846
	Q4	186,993	1,009,610	745,271	242,081	205,795	-	94,454	2,432,254
	Total	**814,333**	**4,059,891**	**2,674,254**	**1,000,833**	**741,783**	**250**	**603,690**	**8,663,004**

Year	Quarter	Bio-blended ULSFO *in tonnes*	Bio-blended VLSFO *in tonnes*	Bio-blended HSFO *in tonnes*	Bio-blended MGO *in tonnes*	Bio-blended MDO *in tonnes*	Bio Methanol *in tonnes*	Bio-blended LNG *in m³*	Bio-blended Subtotal *in tonnes*
2024	Q1	27,263	174,301	42,761	13,180	5,129	-	-	262,635
	Q2								
	Q3								
	Q4								
	Total	**27,263**	**174,301**	**42,761**	**13,180**	**5,129**	**-**	**-**	**262,635**
2023	Q1	1,644	125,982	10,626	8,554	2,400	-	-	149,206
	Q2	3,039	144,970	25,487	10,028	2,300	-	-	185,824
	Q3	7,183	143,677	17,046	14,385	958	250	-	183,499
	Q4	21,974	185,309	9,704	13,469	2,151	500	-	233,108
	Total	**33,840**	**599,938**	**62,864**	**46,436**	**7,810**	**750**	**-**	**751,638**
2022	Q1	9,520	137,051	819	11,998	365	-	-	159,753
	Q2	21,153	119,174	18,679	8,617	1,002	-	-	168,624
	Q3	8,793	144,219	30,462	5,699	3,562	-	-	192,735
	Q4	6,474	234,465	20,140	6,533	1,914	-	-	269,739
	Total	**45,940**	**634,909**	**70,100**	**32,846**	**6,844**	**-**	**-**	**790,851**
2021	Q1	5,223	38,701	20,945	2,511	1,573	-	-	68,953
	Q2	6,010	17,338	17,844	7,265	5,348	-	-	53,805
	Q3	6,941	22,355	11,777	6,354	4,198	-	531	51,864
	Q4	13,650	71,148	18,665	17,904	5,302	-	-	126,669
	Total	**31,824**	**149,542**	**69,230**	**34,034**	**16,421**	**-**	**531**	**301,290**

Figure 7: Bunker sales port of Rotterdam (Port of Rotterdam, 2024)

APPENDIX B

Rapeseed methyl ester (RME)		Mass based accounting for emissions conversion	Source
Rapeseed (kg)	1000	-	-
rapeseed to oil conversion rate	0.333	0.333	ETIP BIOENERGY, n.d.
rapeseed oil to biodiesel(RME)	0.915	0.915	Malça et al., 2014
biodiesel(RME) energy content (MJ/kg)	37.1	-	
energy content RME per tonne of rapeseed (MJ)	11315.5	-	-

Tabel 1: Biodiesel energy conversion and accounting

Feedstock	biomethanol (L) / ton of feedstock	Energy content of methanol (MJ/L)	Energy per tonne (MJ)
Sugar beets	104.6	22	Foteinis et al., 2011

Tabel 2: Biomethanol energy conversion and accounting

Biofuel	Feedstock	Value based accounting % of crop value	Feedstock requirements per kg of fuel	Byproduct ratio (per unit of primary product)
Bioethanol	Wheat straw	28.1 (Wang et al., 2013)	3.982081 (Borrion et al., 2012)	0.61 (Borrion et al., 2012)
Biomethanol	Corn straw	11.8 (Wang et al., 2024)	4.5(Wang et al., 2024)	1.6(Wang et al., 2024)
Biodiesel	UCO	0	1.077	x

Tabel 3: Alternative biofuels energy conversion and accounting