Energy Transition
Radarweg 60
1043 NT Amsterdam
The Netherlands

www.tno.nl

T +31 88 866 50 10

TNO report

TNO 2022 P10286

GHG emissions of innovative technologies in industry - a full value chain approach

Date	11 February 2022
Author(s)	Ayla Uslu Carina Oliveira Milena Brouwer- Milovanovic Jonathan Moncada
Number of pages	53 (incl. appendices)
Number of appendices	3
Sponsor	Ministry of Economic Affairs and Climate (EZK)
Project name	
Project number	

Preface

The authors are thankful to Sander Kes, Peter Besseling and Natalya Rijk (EZK), Ton van Dril, Toon van Harmelen, Anna Schwartz, Julie Cammell, and Mark Roelands (TNO) for their support and constructive feedbacks.

Executive Summary

Background and objectives
The current Dutch policy instruments designed to reduce greenhouse gas (GHG) emissions in industry are targeted only at reducing direct emissions from industry, i.e. scope 1 emissions. Scope 2, or indirect emissions related to the purchase of energy are addressed through a range of other policy instruments focusing on reducing emissions in the energy sector. However other indirect emissions, both downstream and upstream, are not well covered by existing Dutch policies, especially when they occur outside of the Netherlands. These emissions are termed as scope 3 and according to the GHG Protocol, for many companies, substantial emissions linked to their processes may occur outside the company's direct operation. By only focusing on emissions reduction options within scope 1 and 2, there is a risk that a considerable proportion of the overall global GHG emissions impacts are overlooked and the options for reducing emissions, either in the Netherlands or aboard are ignored.

Studies (TNO, 2018) show that there is considerable potential for emissions reduction with measures that aim for indirect emissions reductions, including scope 3 emissions, in addition to direct emissions reduction. However, there are multiple uncertainties about how to consistently determine the actual effect of the scope 3 emissions (TNO, 2018).In addition to that, there are currently no consistent policies in place to incentivise or regulate these scope 3 emission reductions.

This study aims to support the policy making process by developing further knowledge on the full chain GHG effects of circularity measures and biobased options, from scope 1 through to scope 3. Addressing both the direct and indirect emissions may reveal a multitude of new opportunities to reduce GHG emissions and avoid any possible adverse indirect effects and problem shifting.

Development of a harmonised approach for GHG emissions accounting
The literature review conducted at the beginning of this study revealed the need for a transparent and harmonised approach that enables a fair comparison of different innovative value chains with fossil fuel-based references. This study therefore presents a practical and harmonised approach to incorporate the most important steps of the life cycle GHG emissions. It not only enables the presentation of emissions that occur in different steps of the value chain, but also categorises them as scope 1, 2 and 3. This scoping is undertaken from the perspective of the company, where the conversion to intermediate bulk chemicals happens. These emissions are further distinguished as occurring either within the national borders of the Netherlands, or outside of the Netherlands to present the possible upstream and downstream consequences of an industrial activity in the Netherlands. This approach focuses the technology implementation in the Netherlands, to provide a good basis for policy making. This approach can be applied to many different technologies to map out the chain effects of circular and biobased measures in industry and support the policy making regarding the implications of different scopes of emissions

Two cases are presented to illustrate how this approach can be implemented and what insights can be extracted. These are ethylene production from biomass and

from chemically recycled plastics. Ethylene is selected because it is one of the most important petrochemical building blocks. In a further research, other innovative cases for industry can be studied.

Implementation and results of this approach for two cases

Case study results indicate that both biobased ethylene production through the use of sugarcane ethanol, and the production of ethylene through chemical recycling, results in GHG emissions savings when these value chains are compared with the fossil-fuel based reference scenarios.

Figure 1 and Figure *2* illustrate the range of emission savings when compared with the fossil-fuel based reference scenarios. The fossil-fuel based reference scenarios for the two cases were the production of ethylene using virgin naphtha with an end-of-life of either incineration or mechanical recycling. The presented ranges relate to the end-of-life stage and whether this stage occurs in the Netherlands or outside.

Biobased ethylene value chains, illustrated in Figure 1, result in emission savings of 77-90%, when compared with the fossil-fuel based references. This increases to 88-96% in 2030 when some improvements are considered, such as lower emissions in transport, ethanol to ethylene efficiency increase, use of green hydrogen to supply heat to the furnaces, and the incorporation of the lower-emissions intensity 2030 grid electricity mix in the Netherlands. The chemical recycling for this option is not assessed in this study, but such an option would certainly result in even higher emission savings.

The results confirm that scope 3 emissions have a large contribution in total value chain emissions. For the biobased case study these emissions contribute to 48-67% of the total GHG emissions of the biobased value chains. Major contributors to GHG emissions are sugarcane production and overseas ethanol transport to the Netherlands.

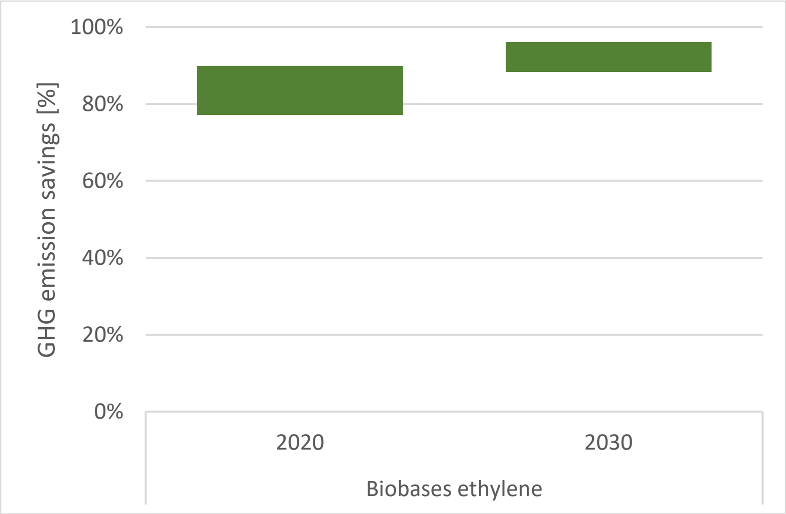

Figure *1*. Life cycle GHG emissions savings of biobased ethylene production in 2020 and 2030. *2030 refers to only the cases where the end-of-life occurs in the Netherlands. That is why the range is smaller.

Emission savings related to ethylene production from plastic pyrolysis oil in Figure *2* relates to two distinct value chains. One of the value chains, illustrated in dark blue, incorporates a continuous circularity via chemical recycling. In this case, feedstock supply consists of sorting of plastic waste and pyrolysis of these to be used as feedstock in the naphtha crackers. The end-of-life of this value chain consists of pyrolysis and mechanical recycling. The mono-plastic streams are considered to be treated via mechanical recycling and the mixed material streams would be directed to pyrolysis in this case. Incineration takes place to address the material losses. This circularity option results in 63-75% emission saving. When the end-of-life of this value chain is mechanical recycling, as is the case in the second value chain presented in light blue, lower emission savings are calculated, around 15-43%. This lower emissions savings relate to the plastic wastes that cannot be treated via mechanical recycling and therefore considered to be incinerated[1]. In case the chemical recycling is implemented in a linear value chain, which means that the recycled ethylene ends up in incineration rather than being recycled again, the emission savings can be very low and even negative. This highlights the significant importance of increased recycling in the system.

In the recycling cases, scope 3 emissions from the perspective of the ethylene refinery include the feedstock supply and the end-of life processes. The pyrolysis step produces the largest GHG emissions, as pyrolysis is an energy-intensive process. These emissions are calculated for present and can be reduced in the future as illustrated in Figure *2*, with future improvements in plastics sorting and increased pyrolysis material efficiency, and both green hydrogen and the lower-emissions intensity 2030 grid electricity mix use. The case with the continues circularity illustrated in dark blue results in more than 100% GHG emission savings in 2030. The scope 3 emissions (end-of-life) of this value chain can reach negative values, mainly because the end-of-life is a combination of chemical and mechanical recycling techniques and more carbon is kept within the system boundary.

The GHG emissions savings range in 2030 is smaller than in 2020 because the future values refer only to the cases where the end-of-life occurs in the Netherlands.

[1] As the focus of this study was on chemical recycling, an improved sorting that that favours higher mechanical recycling is not included into this assessment.

while 2020 range also includes those cases in which the end-of-life happens outside the country.

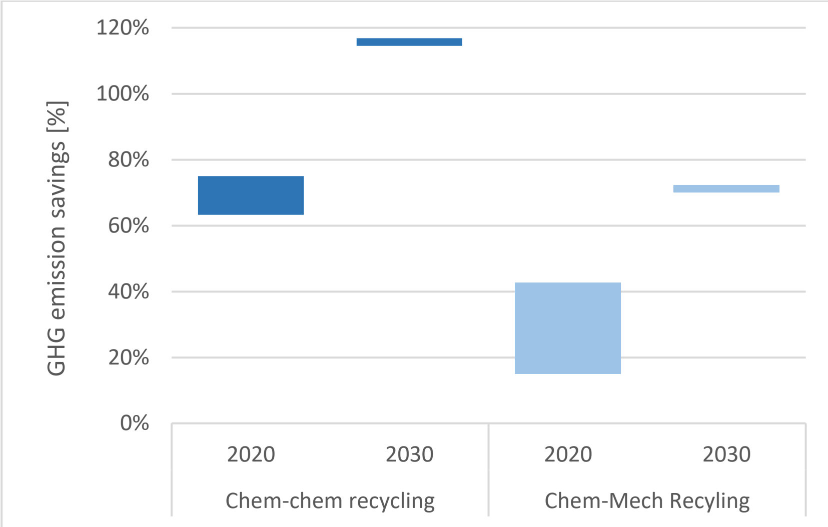

Figure *2*. Life cycle GHG emissions savings of production of ethylene via chemical and mechanical recycling in 2020 and 2030. *2030 refers to only the cases where the end-of-life occurs in the Netherlands.

How to deal with the scope 3 emissions

Existing national policies are focused only on reducing emissions within the Dutch borders and there are good reasons for that. However, when it comes to the production of tradable goods, there is no certainty that these goods will also be consumed in the Netherlands. In fact, a large amount of the produced ethylene in the petrochemical industry is exported. This means that a significant amount of biobased or circular ethylene produced in the Netherlands will likely also be exported to other countries and consumed there, resulting in emission savings occurring elsewhere. Next to that, feedstock supply can also be outsourced. In the case study included in this research, for instance, bioethanol is imported from Brazil.

The existing policy framework in the Netherlands and in Europe already covers some of the scope 3 emissions of the companies. For instance, the transport related emissions in Europe fall under the transport sector emissions reduction objectives. Emissions related to plastic pyrolysis oil production can fall under the EU ETS as these emissions will become scope 1 emissions of the pyrolysis plant, which is an energy intensive industry. Feedstock imported from outside of the EU to produce biobased chemical building blocks and related emissions are more difficult to address by EU and Dutch policies. A possible EU-wide target or obligations for the use of renewable raw materials and recycled materials in the chemical and plastics industries could have major impacts on the scope 3 emissions from these industries. When such an obligation is accompanied with a life cycle GHG emissions threshold as part of a certification, the upstream emissions that may occur aboard can be addressed. In addition, market demand for renewable and circular carbon can be supplemented by a systematic expansion of recycling in Europe. This can help reducing emissions related to the-end-of life. Such instruments, nevertheless, will not avoid any possible scope 3 emissions occurring outside of the EU.

Key messages

Key take home messages on the work presented in this report are presented as follows:

- The approach presented in this report (which is based on the LCA principles), can be adopted and applied to potential value chains to assess the impacts of scope 1, 2 and 3 emissions, and their reductions compared to a fossil-fuel based reference value chain.
- A dynamic tool, where this approach is implemented, should be developed to analyse and assess life cycle emissions in different systems across different time horizons.
- Scope 3 emissions of companies can be substantial and even be the major contributor of life cycle emissions compared to scope 1 and 2 emissions.
- Results show that there are important differences in emissions happening in the Netherlands or abroad. As the Dutch industry is currently in transition and expected to change structurally, technology changes at plant level can result in completely different upstream and downstream routes to the existing ones. This, therefore, has a large influence on potential emission savings when looking into relevant value chains for transforming industry.
- Results of the case studies show that end-of-life treatment is a key value chain step and depending on which technologies are adopted for that purpose, emissions savings can be highly impacted. Even in alternative production chains, recycling of material is key to increase emissions savings when compared to conventional systems. By definition the emissions that occur during the end-of-life are scope 3 emissions.
- Since climate change is a global problem, care should be taken to ensure that policy instruments should at least not lead to unintended and counterproductive effects on scope 3 emissions. This can only be guaranteed if structural instruments covering life cycle emissions are used instead of just scope 1 emissions at plant or company level.

Contents

1 Introduction

1.1 Background

The current policy instruments targeted at industry in the Netherlands are aimed at measures that reduce their direct, on-site emissions. The Greenhouse Gas (GHG) Protocol that provides guidance for industries refers to those emissions as Scope1. Company emissions associated with the supply of electricity, steam and heat to the processes are referred to as scope 2. Company indirect emissions upstream and downstream, referred to as scope 3, are often overlooked. According to the GHG Protocol, for many companies, substantial emissions linked to their production may occur outside the companies gates. By only focusing on emissions reduction options within scope 1 and 2, there is a risk that a considerable proportion of the overall global GHG emissions impacts are overlooked, and the options for reducing these emission are ignored. An industrial actor can take actions to reduce company emissions outside its site perimeters, such as use less energy intensive feedstocks, reduce transportation for its materials and products. Such actions will reduce their Scope 3 emissions. However, there are currently no such policies in place to incentivise and/or regulate these scope 3 emissions.

Studies show that there is considerable potential for emission reductions with measures that aim at full value chain emissions reduction[2]. However, there are multiple uncertainties about how the actual emissions reduction effects in the value chains can be determined consistently (TNO, 2018).

This issue and the need for knowledge development are also recognised in the Climate Agreement. A better understanding of complete value chain effects of measures is necessary to support the decision-making process and design of policy instruments. Addressing full value chain emissions may reveal a multitude of new opportunities to reduce GHG emissions and avoid any possible adverse indirect effects and problem shifting. The Ministry of Economic Affairs and Climate Policy (EZK) has received suggestions from companies about the viable options to reduce CO_2 emissions that have scope 2 and 3 effects in the context of biobased and circular value chains. These emissions can occur in the Netherlands or abroad. In this context, we were requested to conduct an assessment, where full value chain emissions (scope 1, scope 2 and scope 3 emissions) can be studied in detail. Beside the current implementation the assessment should also investigate the implementation in 2030 and beyond.

1.2 Purpose and the scope of this study

The main objective of this study is to support policy makers by developing further knowledge on the full chain GHG effects of biobased and circular options. This fulfils the need for a transparent and harmonised approach that enables a fair comparison of different innovative value chains, as well as a comparison with the fossil- fuel based alternatives, under the same assumptions. Moreover, this approach should reflect the emissions occurring in the Netherlands and abroad.

The dedicated approach for accounting full value chain GHG emissions was developed using the Life Cycle Assessment (LCA) methodology with extension to

[2] TNO has calculated that, if the (value) chains are considered in an international context, then the global emission reduction for 2030 and 2050 is 7.8 and 14.0 Mtonne CO_2 respectively.

GHG scoping. The approach is a stepwise framework, ensuring a consistent methodological basis from which to design value chains for comparison. The insights from the literature review completed at the start of the project were used to shape the approach, mainly by bridging the identified gaps and pitfalls.

To illustrate its functionality, this approach is applied on ethylene, one of the top three chemicals produced worldwide and in the Netherlands. The two value chains with potential to move away from the current linear way of producing ethylene were evaluated: ethylene produced from bioethanol as a case study for the biobased option; and ethanol from plastic waste as a circular option. Different end-of-life options were investigated, as well as a comparison with the fossil-fuel references. Using the same assumptions for each approach allows for emissions of the two value chains to be compared with each other.

1.3 Report outline

This report is divided into five chapters.
- Chapter 1 is a general introduction to the study.
- Chapter 2 introduces the main findings of the literature review on GHG emissions.
- Chapter 3 outlines the approach for accounting full value chain GHG emissions is introduced.
- Chapter 4, introduces the two case studies
- Chapter 5 provides an in-depth analysis of the main results of the case studies.
- Chapter 6 introduces the main discussion points and provides some suggestions with regards to how the introduced approach can assist the existing and possible future policy initiatives.

The report aims to provide a basis from which to answer questions such as:
- What is the current knowledge base regarding GHG emissions accounting approaches and what are the existing blind spots that may be significant for the policy making process? (Chapter 2)
- What can be a consistent and practical approach for the evaluation of Dutch initiatives with scope 3 effects? (Chapter 3)
- What are the emissions reduction potentials? (Chapter 4 and 5)
- What are the policy options and implications to include initiatives with scope 3 effects in current climate? (Chapter 6)

2 Main conclusions of the literature review

A literature review was conducted to identify the methodological blind spots regarding the GHG emissions calculations of biobased and circular value chains. In collaboration with the Ministry, a list of relevant literature was identified for this review. This literature included studies that were recently published (from 2018 onwards) and covered one or more of the value chains suggested by EZK as priority value chains. This review covered the following value chains:

- Biobased options in chemical industry
- Electric cracking in the petrochemical and refinery sectors
- Chemical recycling of plastics via pyrolysis
- Synthetic fuels production.

This chapter provides the main conclusions that are most relevant to this study. The detailed review can be found in Appendix A.

The literature reviewed focused on the conducting of LCAs of innovative technologies or products. One of the main conclusions is that the existing literature neither presents a breakdown analysis of emissions by scope, or provide detailed data to distinguish between the emissions, which is one of the objectives of this study.

Another important conclusion is that the existing analyses relate to a geographical and temporal scope that may not be relevant for evaluation of emissions in the Netherlands at present. Most of the studies on biobased value chains and on chemical recycling have a broader European Union (EU) focus, and LCA calculations used, a dataset representing the EU average. Analyses of value chains for the Netherlands are either missing or covered in a few studies as rough assessments. Furthermore, all the biobased production related literature focuses on the current circumstances. Within the chemical recycling, prospective LCA for 2030 was performed only in one study for Germany.

All reviewed studies follow an LCA approach, nevertheless, they differ greatly in the level of detail and descriptions of the value chains, even for the identical drop ins. These variations relate to the below aspects:

System boundaries & the selected functional units: Among the reviewed studies different system boundaries were set, depending on the main objectives of each study. For instance, cradle-to-grave system boundary, excluding the use phase but including the end-of-life, was implemented to analyse the life cycle impacts of end products such as beverage bottles or single use cups. Since the aim of this study was to compare the potential environmental impacts of the use of alternative feedstock sources for plastic products, GHG emissions were estimated to enable comparison at the level of specific products (rather than its monomer). In some studies a cradle-to-gate approach was used to compare the emissions on monomer level, with a varying degree of detail and the objective. As for end-of-life options (e.g., recycling), the assessment was done in order to evaluate technologies for waste management or as part of the value chain to produce a target chemical. Therefore, the functional units were set as tonnes of mixed plastic waste input from the waste perspective or per tonne of recycled intermediate product from the product perspective. As such, the emissions and savings differed significantly. One study (BASF, 201X) indicated the total emissions reduction to be around 60% from the waste perspective and more than 120% from the product perspective. However, large variations between studies that follow the same perspective were observed, i.e., CE Delft study, 2019 indicated the emissions reduction to be more than 100% from the waste perspective (the same technology was considered, namely chemical recycling via pyrolysis).

Allocation method: Even though almost all studies indicated following the ISO guidelines and adopted system expansion as the first choice followed by subdivision and mass allocation, different data and choices in the allocation provided different results. This highlights the importance of analysing the robustness of methodological choices and understanding whether the GHG emissions impacts are driven by the data that represent the value chain or by the methodological choices adopted.

Accounting method for the CO_2 emissions: Most of the studies account for only fossil carbon, biogenic carbon was rarely accounted for. The studies that focus on cradle-to-grave provided a carbon credit for biobased products, because a short carbon cycle was assumed, and this carbon released to the atmosphere at the end-of-life. CO_2 emissions related to land use and land use change were also rarely accounted for. Moreover, the temporary storage of biogenic carbon and/or delayed emissions of fossil carbon were covered only in one of the reviewed literatures as part of a sensitivity analysis. CO_2 accounting in synthetic fuels relate to the use of CO_2 as feedstock and this was treated very differently in the reviewed studies. Some of the studies considered CO_2 input as credit due to the consideration that the captured CO_2 was fixated. In other studies, CO_2 was either considered as zero emission or emissions related to the capture of CO_2 were attributed as emissions to the synthetic fuel production.

Data sources: Data used can result in different outcomes and care should be taken when drawing conclusions. Some of the studies used primary process data from industry based on current supply chains, but these were kept confidential. These data sources were completed with data from literature, databases such as ecoinvent, GaBi, Plastics Europe and direct communication with experts. The literature for the Netherlands mostly used EU average data. Furthermore, the literature review on synthetic fuels lacks full scale data being an important bottleneck.

Consequently, a need was identified for a harmonized approach to assess the full life cycle GHG emissions of innovative value chains in Dutch industry. This approach should enable comparison among the different options in the context of policy making. Such a comparison will require using the same data sources, setting consistent system boundaries, and balancing the level of complexity. Moreover, such an approach should allow the differentiation of scope 1, 2 and 3 emissions and provide a better understanding of emissions contribution from different value chain stages.

3 Approach for accounting value chain GHG emissions (from an actor perspective in the Netherlands)

A good understanding of the GHG emissions of the circular and biobased options for Dutch industry requires a consistent and transparent accounting approach. This chapter introduces the framework of this approach.

The approach for accounting GHG emissions in circular and biobased value chains follow the steps shown in Figure 3. It is important to note that this approach follows the ISO guidelines for Life Cycle Assessments (ISO, 2006). The steps are described in detail below.

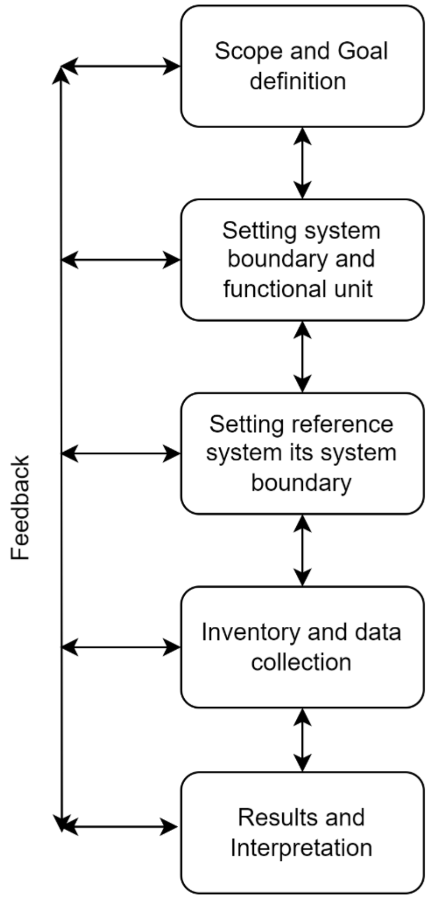

Figure 3. Steps followed in the accounting of GHG emissions in alternative value chains for industry in the Netherlands, from the perspective of the company in focus

3.1 Goal, scope and system boundary setting

The literature review highlighted that many of the LCA studies had different goals, therefore, different system boundaries and functional units. For this study, the goal is to provide a better understanding of GHG emissions in value chains and assess full life cycle emissions. This approach shall identify critical links in emissions within the Netherlands and abroad. Furthermore, the goal is to assess how alternative value chains compare to current fossil options and to identify the stages in the value chain offering the largest emissions savings. This information is key to identifying whether certain value chains are relevant or may become relevant so (as some have not been implemented yet) in the Dutch context even if emission savings happen across the Dutch border. The approach is illustrated in the case studies presented later in the report.

The system boundary includes feedstock production and supply to intermediate conversion, supply of intermediates to the main production and production itself, and end-of-life, including transport.

The approach is flexible, so the users are able to set the system boundary depending on the technology/system to be analysed. For instance, if an actor is interested in assessing upstream and downstream emissions of its activity (scope 3 emissions), a cradle-to-grave approach can be followed. Figure 4 shows an example of a system boundary following a cradle-to-grave approach. It is important to mention that the boundary can be extended to cradle-to-cradle to consider nonlinear options such as those for circular technologies. However, they can also be limited to cradle-to-gate approach if downstream operations are not important. Also, system boundaries can be adapted in case there are multiple intermediate production steps and multiple feedstock inputs, which lead to branched systems instead of linear systems.

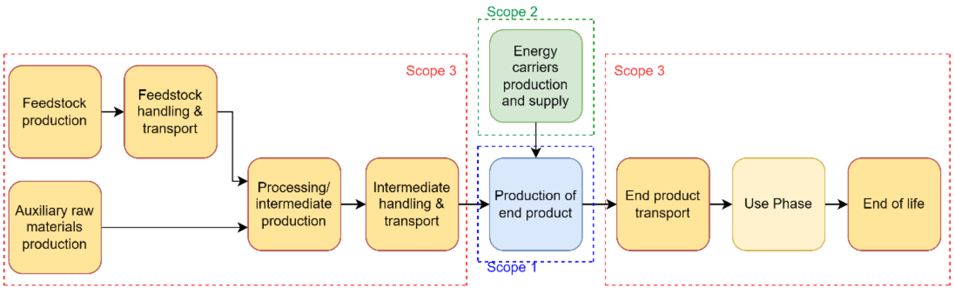

Figure 4. Example of system boundary for a generic value chain, viewed from the company in focus

Please note that the system boundary can be adjusted to any type of value chain, and those steps that are not relevant can be omitted. A brief explanation of the steps considered within the system boundary depicted in Figure 4 is presented below.

- Feedstock production/extraction. Operations such as the collection and sorting of the feedstock should also be included in this stage. It is important to note that if multiple feedstocks are used, emissions related to those activities should also be included.
- Handling of the feedstock. Depending on the value chain this can be drying and pre-treatment, and the conversion of feedstocks into intermediates (include if required).
- Production of auxiliary raw materials. These are materials that can be used during the pre-treatment and conversion to intermediates. In case there is no need for auxiliary materials, this step can be omitted. In case more intermediate production steps are involved those can be included in the system boundary.

- In some cases, transport of intermediates to the final conversion step into the product of interest is also required. If this is the case it is included within the system boundary, as in the example depicted in Figure 4. In other cases, intermediates might be produced just next door to the final conversion and if not required the step can be excluded from the system boundary.
- Final conversion step is performed by the company in focus. The company is assumed to be in the Netherlands and the functional unit is defined based on the product.
- Production and supply of energy to different processes in the value chain are also accounted for in the approach. For instance, emissions related to the production and supply of energy to extract raw materials are embedded within the feedstock production. The approach therefore includes all cradle emissions of the steps included within the system boundaries.
- Transport of feedstocks, intermediates and the end product are included in relevant steps of the supply chain. When any of the steps becomes irrelevant, they can be omitted.
- Use phase is excluded from the current approach as this phase is considered to be identical between the options. Depending on the selected value chain, when needed, the use phase can also be included within the system boundaries.
- End-of-life emissions is the last step included within the system boundaries. End-of-life emissions depend on the type of technology used to treat the product at its end-of-life.
- The aggregation of the emissions of the different steps gives total value chain emissions.

3.2 What are scope 1, 2 and 3 emissions in this context and why are they included in this approach

Emissions accounting using scope 1, 2 and 3 has been a widely used approach for corporate emissions reporting. According to the GHG Protocol Corporate Standard, scope 1 emissions are direct emissions from owned or controlled sources; scope 2 emissions are indirect emissions from the generation of purchased energy; and scope 3 emissions are all indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions. Thus, scope 3 emissions can be a consequence of the activities of the company, but can occur from sources not owned or controlled by the company. The issue on reporting in scopes is that in many cases reporting depends on the perspective and how emissions are accounted for. Scope 1 and 2 emissions of a certain company can be classified as scope 3 emissions of another company. Scope 3 emissions can happen inside or outside The Netherlands.

It is important to mention that the system boundary needs to be aligned with the goal (e.g., an understanding of downstream and upstream emissions) of the case study as well as its scope (e.g., the temporal frame, region).

Emissions accounting per scope is not reported in initially reviewed literature. This is because those studies aimed to present the life cycle impacts of a certain product rather than the company that produces it or full life cycle emissions. Using the approach outlined here, in addition to the emissions per product, the emissions per different scope can be presented. In this way, the approach supports the policy makers in understanding the full value chain emissions of companies in the Netherlands. Consequently, it can support policy instruments that enforce companies to focus their efforts on the greatest GHG emissions reduction opportunities.

3.3 Selection of functional unit and reference system

Selection of functional unit
In the current approach, the functional unit needs to be chosen in accordance with the system boundaries, which should reflect the goal and scope of the case to be analysed.

The functional unit acts as the quantification standard. It should be identical for analysed scenarios, allowing comparison on the same bases. This would also allow a comparison with reference systems.

Product perspective was chosen in this study as it gives the equal basis for comparison between scenarios as well as between different value chains for the same target product.

Selection of reference system
When assessing alternative options for producing a target product, it is very important to compare it with a reference system. In general, the reference system refers to conventional production. Consistency in comparison is key in order to draw conclusions on emissions reduction potentials when implementing an alternative to a conventional system. In this approach, the system boundary of the reference system includes similar production steps as the alternative system assessed and its functional unit is identical.

3.4 Dealing with multifunctionality (multiproduct systems)

Multifunctionality (typical in multiproduct systems) refers to the coexistence of other products with the main product, sharing certain processes in the value chain. This means that the emissions linked to the process need to be shared between the different products. A good example of this are the emissions related to olefins production, in which the total GHG emissions are attributed to multiple valuable streams. To do this different allocation approaches can be used, and in some cases depending on the choices made interpretation of results can vary significantly. This issue was also observed in the literature review.

This study follows the ISO guidelines on Life Cycle Assessment and their recommendations on dealing with multifunctionality (ISO, 2006).
- ISO guidelines advise to use system expansion as a first choice, which in broad terms relates to the use of emission credits in co-products assuming that they will substitute a meaningful conventional product. A good example of this is, for instance, if electricity is a co-product in a complex multiproduct system, emissions credits are obtained by the assumption that this electricity substitutes electricity from the grid. When conducting the accounting on product substitution, double counting should be avoided. System emissions minus the credits by products substitution of the co-products yields the emissions to the meaningful product of the company in focus.
- There are cases in which the systems are very complex and system expansion is not straight forward and sometimes not possible. For instance, in systems where the co-products are not drop-ins to conventional products. In those

cases, distribution by physical properties is recommended. For instance, based on the share of energy of each product on the overall energy output of the system, or the share of mass on the total mass leaving the system in valuable products. If this is still not possible, the last option is to carry out allocation by using economic values, for instance the share of product revenues on total system revenues (ISO, 2006). The shares are often called ‘allocation factors’ in literature, and they determine the percentage to which total emissions of the system are attributed to certain product of the value chain in interest.

3.5 Inventory data and data sources

Inventories refer to process data and emission factors used to account for GHG emissions of the different stages of the value chains, as those shown in the example in *Figure 4*. Data related to the different steps is generally gathered from literature, but the current approach allows for complete inventories with primary data to be used where available. These data should reflect on important parameters to quantify mass and energy flows of the different steps, for instance reflecting energy consumption, conversion efficiencies, plant capacities and direct GHG emissions. These data are constrained in assumptions about time, geography, and technology. Assumptions and specifications of the value chains assessed in this study are discussed in more detail in Appendix B. Detailed inventory data of the value chains assessed in the case studies is presented in detail in Appendix C.

To be able to translate mass and energy flows into GHG emissions, characterization factors were used. Those were gathered primarily from databases such as ecoinvent v3.7 (Ecoinvent, 2020), and complemented with data from the SDE++ (PBL, 2021b) and KEV 2021 (PBL, 2021a) for specific Dutch emission factors of certain inputs such as electricity and steam. The dataset used for the cases can be found in the calculation tool, where the detailed calculation and the references of the dataset are presented.

GHG emissions are calculated using the method IPCC 2013 GWP 100a based on Global Warming Potential (in kgCO_2-eq). Only fossil CO_2 is accounted for, and biogenic CO_2 emissions are treated as neutral[3].

Time dependency

The approach used, allows for the carrying out of assessments for the current situation, assuming that alternative production systems would be implemented today (baseline) and for future scenarios. This implies that emission factors can reflect today's situation and to the extent possible future performances. The emission factors change over time, and in the case of electricity from the grid, the emission factor will be lower as the sector decarbonizes. Also, technology

---

[3] Biogenic carbon neutrality refers to the assumption that that biogenic CO_2 emitted during any activity of biobased value chains is eventually sequestered back during plant growth resulting in zero net emissions. In LCA approaches this has been a common practice and thus biogenic emissions are omitted in the accounting of carbon emissions. In the current study, we opted to use this approach as it is highly adopted in LCA oriented studies. It can however be argued that biogenic emissions are not always neutral and time frames for recapture may be lagging behind when compared to the rate at which those are emitted. To assess this, dynamic carbon accounting methods should be used.

performance can improve over time. In this approach, the relevant time perspectives must be taken into account. The database includes emission factors for 2020 and 2030 based on the KEV projections.

Current approach does not include the lifetime of the product in use. Moreover, the possible carbon storage in products and the dynamic behaviour of biogenic carbon emissions are not captured in the current approach (ISO, 2006). This approach for this study will need to be updated in case the climate change impacts are to be calculated for shorter than 100 years, or if the end product is considered to be stored longer than 100 years.

4 Case studies

A good understanding of the GHG emissions of the circular and biobased options for Dutch industry requires a consistent and transparent accounting approach. This chapter introduces the framework of this approach.

The approach for accounting GHG emissions in circular and biobased value chains follow the steps shown in Figure 3. It is important to note that this approach follows the ISO guidelines for Life Cycle Assessments (ISO, 2006). The steps are described in detail below.

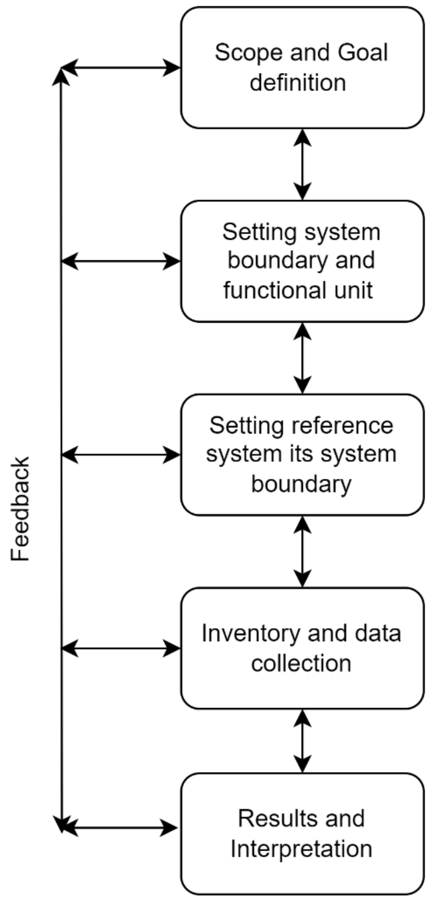

Figure 5. Steps followed in the accounting of GHG emissions in alternative value chains for industry in the Netherlands, from the perspective of the company in focus

4.1 Goal, scope and system boundary setting

The literature review highlighted that many of the LCA studies had different goals, therefore, different system boundaries and functional units. For this study, the goal is to provide a better understanding of GHG emissions in value chains and assess full life cycle emissions. This approach shall identify critical links in emissions within the Netherlands and abroad. Furthermore, the goal is to assess how alternative value chains compare to current fossil options and to identify the stages in the value chain offering the largest emissions savings. This information is key to identifying whether certain value chains are relevant or may become relevant so (as some have not been implemented yet) in the Dutch context even if emission savings happen across the Dutch border. The approach is illustrated in the case studies presented later in the report.

The system boundary includes feedstock production and supply to intermediate conversion, supply of intermediates to the main production and production itself, and end-of-life, including transport.

The approach is flexible, so the users are able to set the system boundary depending on the technology/system to be analysed. For instance, if an actor is interested in assessing upstream and downstream emissions of its activity (scope 3 emissions), a cradle-to-grave approach can be followed. Figure 4 shows an example of a system boundary following a cradle-to-grave approach. It is important to mention that the boundary can be extended to cradle-to-cradle to consider nonlinear options such as those for circular technologies. However, they can also be limited to cradle-to-gate approach if downstream operations are not important. Also, system boundaries can be adapted in case there are multiple intermediate production steps and multiple feedstock inputs, which lead to branched systems instead of linear systems.

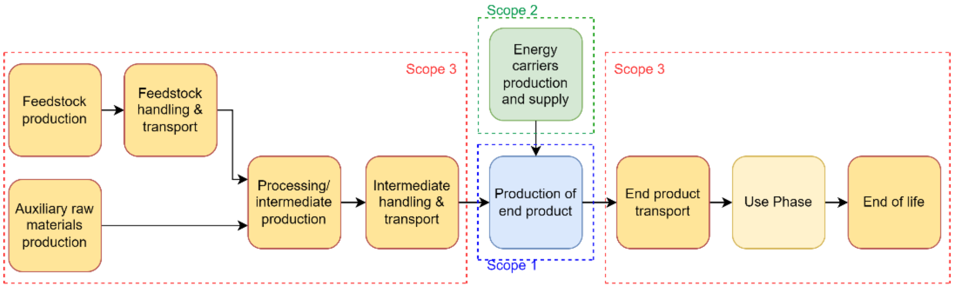

Figure 6. Example of system boundary for a generic value chain, viewed from the company in focus

Please note that the system boundary can be adjusted to any type of value chain, and those steps that are not relevant can be omitted. A brief explanation of the steps considered within the system boundary depicted in Figure 4 is presented below.

- Feedstock production/extraction. Operations such as the collection and sorting of the feedstock should also be included in this stage. It is important to note that if multiple feedstocks are used, emissions related to those activities should also be included.
- Handling of the feedstock. Depending on the value chain this can be drying and pre-treatment, and the conversion of feedstocks into intermediates (include if required).
- Production of auxiliary raw materials. These are materials that can be used during the pre-treatment and conversion to intermediates. In case there is no need for auxiliary materials, this step can be omitted. In case more intermediate production steps are involved those can be included in the system boundary.
- In some cases, transport of intermediates to the final conversion step into the product of interest is also required. If this is the case it is included within the system boundary, as in the example depicted in Figure 4. In other cases,

intermediates might be produced just next door to the final conversion and if not required the step can be excluded from the system boundary.
- Final conversion step is performed by the company in focus. The company is assumed to be in the Netherlands and the functional unit is defined based on the product.
- Production and supply of energy to different processes in the value chain are also accounted for in the approach. For instance, emissions related to the production and supply of energy to extract raw materials are embedded within the feedstock production. The approach therefore includes all cradle emissions of the steps included within the system boundaries.
- Transport of feedstocks, intermediates and the end product are included in relevant steps of the supply chain. When any of the steps becomes irrelevant, they can be omitted.
- Use phase is excluded from the current approach as this phase is considered to be identical between the options. Depending on the selected value chain, when needed, the use phase can also be included within the system boundaries.
- End-of-life emissions is the last step included within the system boundaries. End-of-life emissions depend on the type of technology used to treat the product at its end-of-life.
- The aggregation of the emissions of the different steps gives total value chain emissions.

4.2 What are scope 1, 2 and 3 emissions in this context and why are they included in this approach

Emissions accounting using scope 1, 2 and 3 has been a widely used approach for corporate emissions reporting. According to the GHG Protocol Corporate Standard, scope 1 emissions are direct emissions from owned or controlled sources; scope 2 emissions are indirect emissions from the generation of purchased energy; and scope 3 emissions are all indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions. Thus, scope 3 emissions can be a consequence of the activities of the company, but can occur from sources not owned or controlled by the company. The issue on reporting in scopes is that in many cases reporting depends on the perspective and how emissions are accounted for. Scope 1 and 2 emissions of a certain company can be classified as scope 3 emissions of another company. Scope 3 emissions can happen inside or outside The Netherlands.

It is important to mention that the system boundary needs to be aligned with the goal (e.g., an understanding of downstream and upstream emissions) of the case study as well as its scope (e.g., the temporal frame, region).

Emissions accounting per scope is not reported in initially reviewed literature. This is because those studies aimed to present the life cycle impacts of a certain product rather than the company that produces it or full life cycle emissions. Using the approach outlined here, in addition to the emissions per product, the emissions per different scope can be presented. In this way, the approach supports the policy makers in understanding the full value chain emissions of companies in the Netherlands. Consequently, it can support policy instruments that enforce companies to focus their efforts on the greatest GHG emissions reduction opportunities.

4.3 Selection of functional unit and reference system

Selection of functional unit
In the current approach, the functional unit needs to be chosen in accordance with the system boundaries, which should reflect the goal and scope of the case to be analysed.

The functional unit acts as the quantification standard. It should be identical for analysed scenarios, allowing comparison on the same bases. This would also allow a comparison with reference systems.

Product perspective was chosen in this study as it gives the equal basis for comparison between scenarios as well as between different value chains for the same target product.

Selection of reference system
When assessing alternative options for producing a target product, it is very important to compare it with a reference system. In general, the reference system refers to conventional production. Consistency in comparison is key in order to draw conclusions on emissions reduction potentials when implementing an alternative to a conventional system. In this approach, the system boundary of the reference system includes similar production steps as the alternative system assessed and its functional unit is identical.

4.4 Dealing with multifunctionality (multiproduct systems)

Multifunctionality (typical in multiproduct systems) refers to the coexistence of other products with the main product, sharing certain processes in the value chain. This means that the emissions linked to the process need to be shared between the different products. A good example of this are the emissions related to olefins production, in which the total GHG emissions are attributed to multiple valuable streams. To do this different allocation approaches can be used, and in some cases depending on the choices made interpretation of results can vary significantly. This issue was also observed in the literature review.

This study follows the ISO guidelines on Life Cycle Assessment and their recommendations on dealing with multifunctionality (ISO, 2006).

- ISO guidelines advise to use system expansion as a first choice, which in broad terms relates to the use of emission credits in co-products assuming that they will substitute a meaningful conventional product. A good example of this is, for instance, if electricity is a co-product in a complex multiproduct system, emissions credits are obtained by the assumption that this electricity substitutes electricity from the grid. When conducting the accounting on product substitution, double counting should be avoided. System emissions minus the credits by products substitution of the co-products yields the emissions to the meaningful product of the company in focus.
- There are cases in which the systems are very complex and system expansion is not straight forward and sometimes not possible. For instance, in systems where the co-products are not drop-ins to conventional products. In those cases, distribution by physical properties is recommended. For instance, based on the share of energy of each product on the overall energy output of the system, or the share of mass on the total mass leaving the system in valuable

products. If this is still not possible, the last option is to carry out allocation by using economic values, for instance the share of product revenues on total system revenues (ISO, 2006). The shares are often called ‘allocation factors’ in literature, and they determine the percentage to which total emissions of the system are attributed to certain product of the value chain in interest.

4.5 Inventory data and data sources

Inventories refer to process data and emission factors used to account for GHG emissions of the different stages of the value chains, as those shown in the example in *Figure 4*. Data related to the different steps is generally gathered from literature, but the current approach allows for complete inventories with primary data to be used where available. These data should reflect on important parameters to quantify mass and energy flows of the different steps, for instance reflecting energy consumption, conversion efficiencies, plant capacities and direct GHG emissions. These data are constrained in assumptions about time, geography, and technology. Assumptions and specifications of the value chains assessed in this study are discussed in more detail in Appendix B. Detailed inventory data of the value chains assessed in the case studies is presented in detail in Appendix C.

To be able to translate mass and energy flows into GHG emissions, characterization factors were used. Those were gathered primarily from databases such as ecoinvent v3.7 (Ecoinvent, 2020), and complemented with data from the SDE++ (PBL, 2021b) and KEV 2021 (PBL, 2021a) for specific Dutch emission factors of certain inputs such as electricity and steam. The dataset used for the cases can be found in the calculation tool, where the detailed calculation and the references of the dataset are presented.

GHG emissions are calculated using the method IPCC 2013 GWP 100a based on Global Warming Potential (in kgCO_2-eq). Only fossil CO_2 is accounted for, and biogenic CO_2 emissions are treated as neutral[4].

Time dependency

The approach used, allows for the carrying out of assessments for the current situation, assuming that alternative production systems would be implemented today (baseline) and for future scenarios. This implies that emission factors can reflect today's situation and to the extent possible future performances. The emission factors change over time, and in the case of electricity from the grid, the emission factor will be lower as the sector decarbonizes. Also, technology performance can improve over time. In this approach, the relevant time

[4] Biogenic carbon neutrality refers to the assumption that that biogenic CO_2 emitted during any activity of biobased value chains is eventually sequestered back during plant growth resulting in zero net emissions. In LCA approaches this has been a common practice and thus biogenic emissions are omitted in the accounting of carbon emissions. In the current study, we opted to use this approach as it is highly adopted in LCA oriented studies. It can however be argued that biogenic emissions are not always neutral and time frames for recapture may be lagging behind when compared to the rate at which those are emitted. To assess this, dynamic carbon accounting methods should be used.

perspectives must be taken into account. The database includes emission factors for 2020 and 2030 based on the KEV projections.

Current approach does not include the lifetime of the product in use. Moreover, the possible carbon storage in products and the dynamic behaviour of biogenic carbon emissions are not captured in the current approach (ISO, 2006). This approach for this study will need to be updated in case the climate change impacts are to be calculated for shorter than 100 years, or if the end product is considered to be stored longer than 100 years.

5 Results of the two case studies

This section presents the results of the case studies described in section 4 for ethylene production and compared to conventional ethylene. Background data for each value chain is appended to this report (Appendix B). The data describes the mass and energy flows build from the data sources and assumptions presented in Appendix C.

5.1 Ethylene from sugarcane

5.1.1 Life cycle emissions

GHG emissions of the value chain for producing ethylene are compared with fossil ethylene production to evaluate emissions savings potential. Ranges of life cycle emissions of ethylene produced from sugarcane and ethylene produced from naphtha are presented in Figure 7. Results indicate that sugarcane derived ethylene can be up to 77-90% lower than fossil ethylene (under the assumptions and conditions shown in chapter 4). The main difference between biobased and the fossil-fuel based route are the large GHG emissions related to the conversion of naphtha compared to the biogenic emissions of producing ethanol and conversion of it into ethylene. The renewable characteristic of biomass allows for much lower environmental impacts at the feedstock production level, even if large quantities of biomass are required to produced 1 kg of ethylene (35 kg of sugarcane per kg of ethylene produced). The range presented depends on the technology pathways chosen and the end-of-life cases. Details on inventory of data used to calculate emissions are shown in Appendix C.

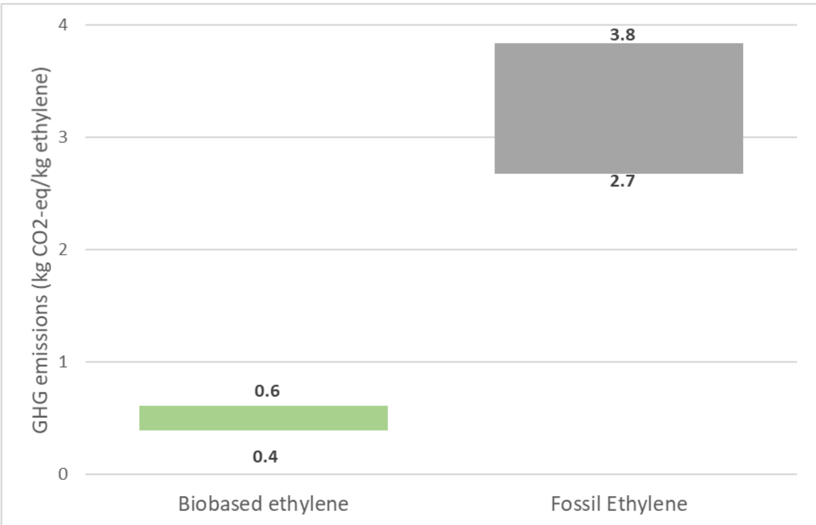

Figure 7. Life cycle emissions of ethylene production from sugarcane and fossil-fuels.

To have a better understanding on what the effect of end-of-life is, Figure 8 presents a ranking (from lowest to highest) on life cycle emissions of the pathways for producing ethylene and its end-of-life treatment. The dark grey columns indicate conventional ethylene production, with the highest emissions being those of incinerating ethylene in the Netherlands. If ethylene is incinerated outside the

Netherlands, emissions are slightly lower. This can be explained by the higher credit (due to slightly higher emission factors for EU averages compared to the Netherlands) regarding heat and electricity substitution in the EU, when compared to the Netherlands. In case mechanical recycling is implemented, emissions of the conventional system decreased up to 30%, in comparison to the cases where incineration is adopted as end-of-life. This, therefore, corroborates the importance of recycling carbon across the value chain. It is important to mention that end-of-life emissions hugely increase the impact of the fossil-fuel based alternatives, compared to their cradle-to-gate emissions. End-of-life emissions accounted up to 46-62% of the total life cycle emissions of the fossil-fuel based reference routes. This suggests the importance of including end-of-life in the analysis, which ultimately depends on setting proper system boundaries and setting a consistent reference system. This allows for fair comparisons and sound decision making about which alternatives are more favourable for a product.

In the biobased product, carbon is accounted for as biogenic, which ultimately does not entirely capture the effect of releasing carbon to atmosphere in the incineration case (emissions reduced by 16%) and does not account for the fact that recycled biogenic carbon can ultimately lead to negative emissions due to the circular characteristic. This represents a methodological challenge of the approach presented in Chapter 3, as the neutrality concept of biogenic emissions has been adopted. Also, this is related to the time frame of carbon circulating through the product chain, which is also a methodological barrier as current LCA practices do not capture delays in value chains and number of recycling cycles. There are ongoing discussions on how biogenic emissions should be accounted in products, and how to properly account carbon in circular options.

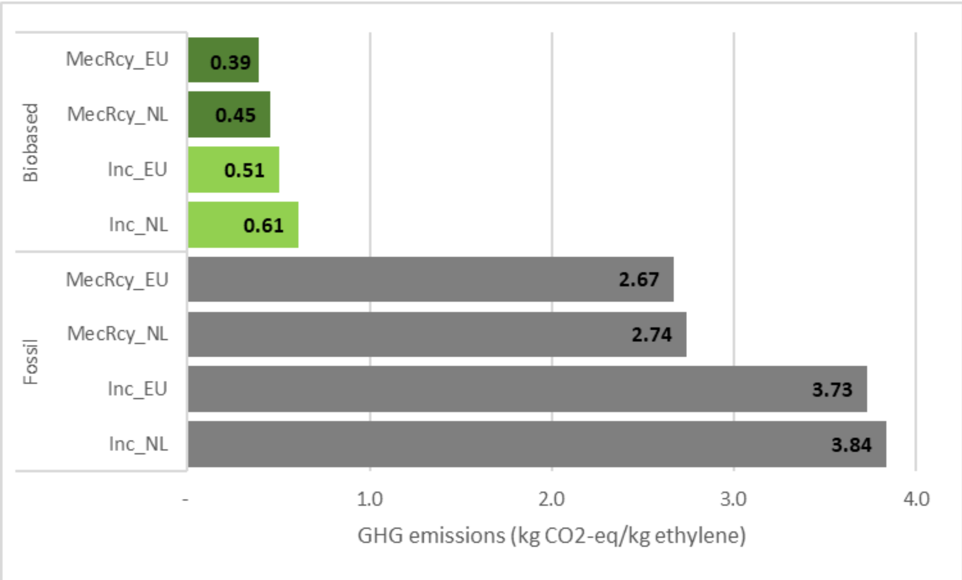

Figure 8. Ranking of bioethylene production in comparison to fossil ethylene. Notations base on end-of-life options. Abbreviations: Inc_NL: incineration in the Netherlands, MecRcy_NL: mechanical recycling in the Netherlands, Inc_EU: incineration in EU, MecRcy_EU: mechanical recycling EU

5.1.2 *Geographical scope of emissions*

One of the questions that arises when assessing GHG emissions at a value chain level is where emissions are happening and what are the main contributors to those emissions. That allows for an understanding on how supply of feedstocks and downstream activities affect emissions of the company in focus. To identify GHG emissions per region Figure 9 can be used.

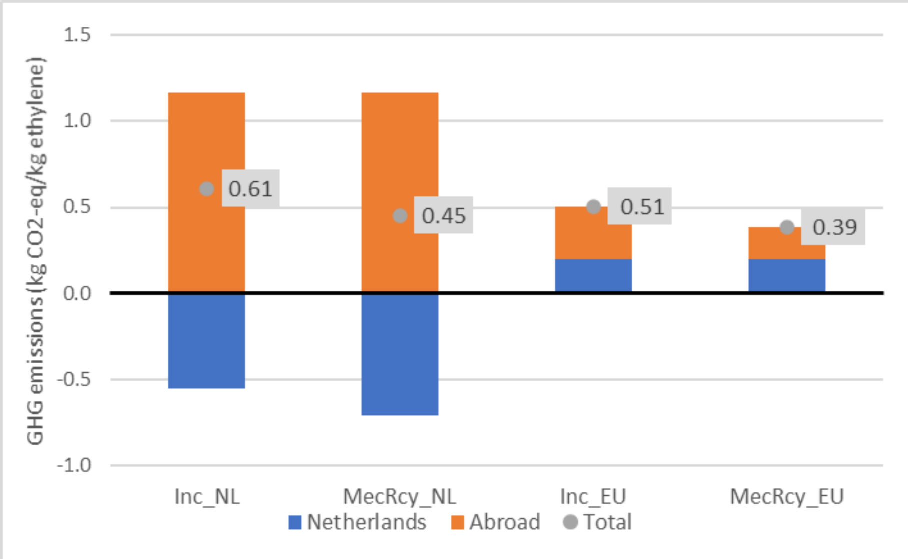

Figure 9. GHG emissions per region of biobased ethylene production.

Figure 10 shows that even though the life cycle GHG emissions are similar for all biobased cases, the direction of emissions per region are different. In all cases of the production of biomass, conversion into ethanol and transport of ethanol happen abroad. In the cases where end-of-life happens in the Netherlands, credits are accounted for in the Netherlands. In the case of incineration, credits come from the electricity and heat use in the Netherlands. In the case of recycling, credits come from the avoidance of producing fossil ethylene, and electricity and heat from the incineration of the non-recyclable fraction of plastic. In short, these two cases account for negative impacts abroad, but only credits in the Netherlands.

Accounting only for emissions happening in the Netherlands and disregarding the emissions occurring abroad can lead to misleading conclusions on the negative emissions of biobased ethylene. Figure 9 shows that abroad emissions overtake negative emissions in the Netherlands and net emissions remain positive.

5.1.3 *Emissions by scope and identification of hotspots*

Results presented so far have focused on the aggregated value chain GHG emissions. The current approach allows for the identification of critical points on a certain value chain and also allows for a breakdown of scope 1, 2 and 3 as described in the system boundaries (see section 4). Division of GHG emissions by scopes is presented in Figure 10. Results show that scope 3 emissions have a large contribution in total value chain emissions, being 3 to 5 times higher than scope 1 emissions and 3-4 times higher than scope 2 emissions. The contribution of scope 3 emissions in total value chain emissions ranges between 48-67% for the cases presented in Figure 10. This clearly shows that scope 3 emissions need to be carefully assessed as those have an important contribution to overall emissions of any value chain. Figure 10 shows that in biobased cases large emission credits happen outside (scope 3) the factory gate of the company in focus, which ultimately plays a major role in determining total value chain emissions.

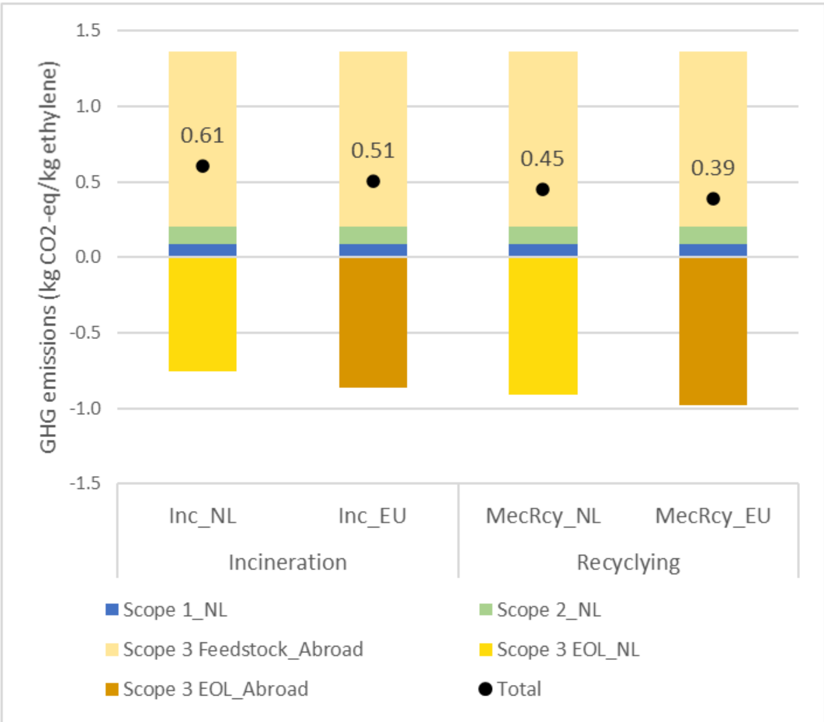

Figure 10. GHG emissions distributed into the different scopes for biobased ethylene production.

The approach presented in chapter 3 also allows for a focus on the major emissions contributors. Figure 11 shows a breakdown on the stages that contribute to full value chain emissions. Significant credits happen outside the factory gate of the company in focus, in this case credits in end-of-life, due to the production of electricity and heat in incineration and the substitution of fossil ethylene production in recycling. Ethanol production also generates credits for co-products generated such as electricity and heat.

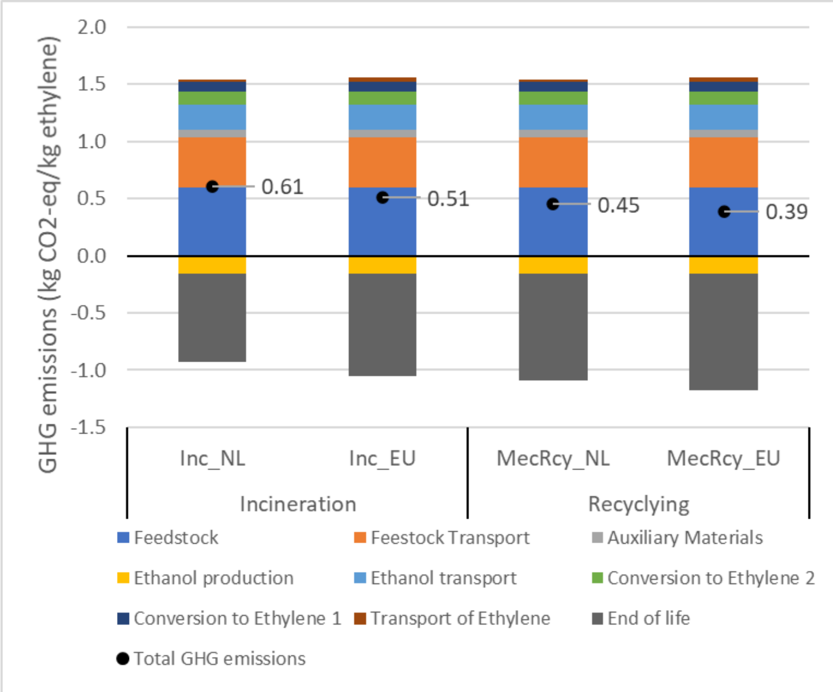

Figure 11. Breakdown analysis of value chain emissions of biobased ethylene production

Results presented in Figure 11 also show that the major contributors to GHG emissions are sugarcane production, sugarcane transport to the ethanol production factory and ethanol transport from Brazil to the Netherlands. All these three operations happen abroad. The contribution of sugarcane production and transport is large as there is an important amount of sugarcane needed to produce ethylene (35 kg of sugarcane per kg of ethylene). Sugarcane emissions are related to machinery use for harvesting, the production and delivery of energy needed for that machinery, emissions related to fertilizer and pesticide use (including energy and upstream emissions of fertilizer and pesticide production), and emissions related to seed production. GHG emissions of sugarcane production do not account for direct and indirect land use change effects which can affect overall GHG emissions of the value chain. This is indirectly assessed in the following section by looking into what is the effect on increasing sugarcane emission factor. Emissions due to ethanol transport are in this case fully related to transport from Brazil to the Netherlands. It would be thus more beneficial to have ethanol production facilities in Europe which can supply ethylene production plants. This, however, can be challenging due to restrictions of land and resources. Thus, in further studies, it would be worth to investigate the effect of feedstock location and feedstock type. Second generation ethanol production was not assessed in this study, but it could be an interesting route to assess in the future.

5.1.4 Sensitivities

As mentioned in the previous section, one of the aspects that is most critical on biomass supply is the uncertainty around land use change effects. As this was not included in the assessment, Figure 12 shows that should sugarcane emissions be increased by 100% as an estimate of the impact of land use change effects, the emissions of biobased ethanol increase up to 1.6-3.1 times when compared to those of the baseline (see section 5.1.1). Even with this sizeable estimated increase in emissions of the biobased routes, compared to the fossil system, emissions of biobased ethylene remain lower up to 55-74%. In addition, large variations of land use change effects can be overcome by using other feedstocks.

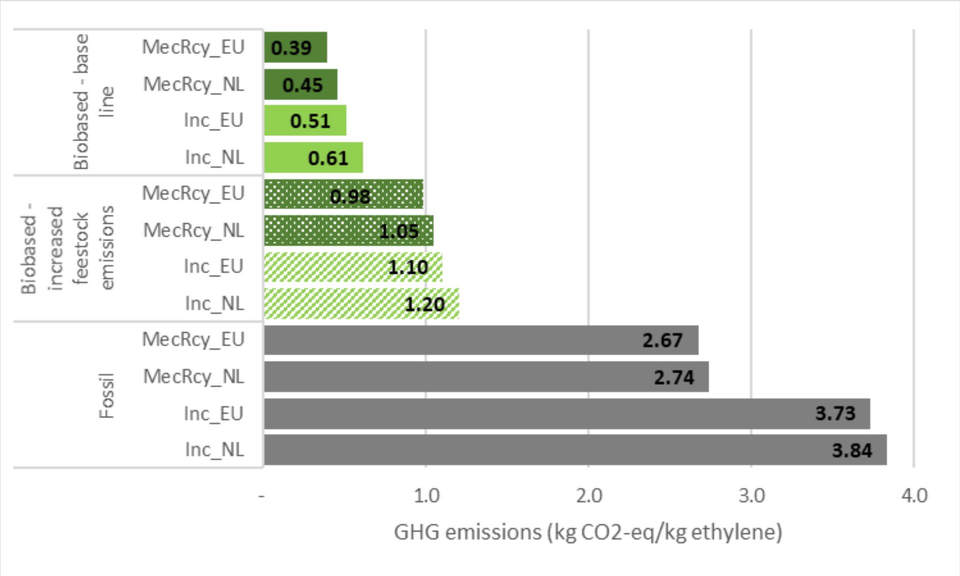

Figure 12. Impact of increased sugarcane GHG emissions on life cycle emissions for biobased ethylene

5.1.5 2030 Scenario

In the current approach, possible future scenarios can be tested and the effect of changes such as process efficiency or emissions related to the feedstock can be observed. For biobased ethylene, the 2030 scenario is based on the identification of hotspots discussed previously in this section. These aspects are described as follows:

i. Transport emissions of sugarcane to the ethanol process were reduced by 30%, assuming that transport of sugarcane can be done more efficiently, and the load transported by each truck increases. Sugarcane emissions were kept identical to the baseline given the uncertainty on land use change effects.
ii. The efficiency of overseas ethanol transport was improved by 30%, assuming that ships become more specialized and can handle higher loading of ethanol (current 80% loading).
iii. The conversion of ethanol to ethylene was increased up to 90% of the theoretical maximum (current conversion rate 0.44 kg ethylene/kg ethanol, improved in 2030 to 0.55 kg ethylene/kg ethanol)
iv. It was assumed that green hydrogen would be the fuel used as heat supply to the furnace in the conversion of ethanol to ethylene.
v. Projected grid electricity emissions based on KEV 2021 (PBL, 2021a) were used.
vi. No changes were made to the end-of-life.

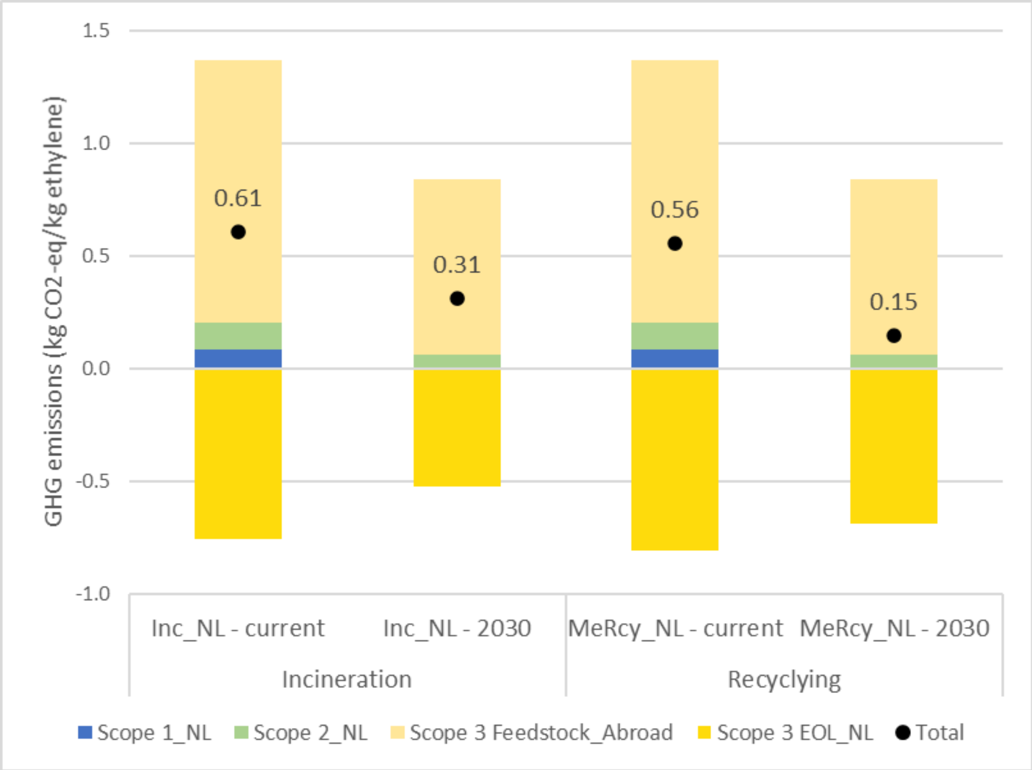

Figure 13. GHG emissions per scope 2030 scenario; cases in which end-of-life occur only in the Netherlands for biobased ethylene

Results displayed in Figure 13 show that under the conditions presented for 2030, emissions of the biobased options compared to the baseline can be decreased by 49% in the case incineration is used, and up to 73 in the case recycling is implemented. Results show that scope 1 emissions are fully eliminated with the use of green hydrogen as fuel for the furnace. Other renewable alternatives for fuelling the furnace could also bring scope 1 emissions down, however this has not been taken into account in this scenario. Scope 2 emissions decrease significantly as electricity from the grid decreases its intensity by 33% in the 2030 case. Emissions in the 2030 scenario are dominated by scope 3 emissions. Scope 3 emissions were also decreased by considering that less biomass is required to produce ethylene due to the ethylene process yield increase (28 kg of biomass per kg ethylene), and by improving the efficiencies of biomass and ethanol transport. In contrast, credits in scope 3 end-of-life emissions are lower compared to the current case. In the 2030 scenario, emissions credits for electricity substitution are much lower as the emissions intensity of electricity from grid is 33% than that of the current emissions intensity of the grid.

5.2 Ethylene production from plastic waste pyrolysis

5.2.1 Life cycle emissions

Emissions of ethylene production using the pyrolysis oil from mixed plastic waste are compared with fossil ethylene production. In Figure 14, ranges of full life cycle emissions between the options are presented.

Results show that in the case where ethylene is produced from pyrolysis oil and incineration at the end-of-life is considered (linear chain), emissions are slightly lower than the high end of the emissions range for the fossil ethylene production. This has mostly to do with the fact that the material efficiency in the conversion of plastic waste to ethylene is still low compared to the fossil-fuel based reference route. In contrast, when recycling is included (by using recycled plastics as feedstock) and end-of-life follows also a recycling step (either mechanical or chemical combined with mechanical), emissions become lower than the fossil-fuel based references (see Figure 14).

When compared to the GHG emissions range of the fossil ethylene, the options including chemical recycling combined with mechanical recycling at end-of-life are 63-75% lower and the options with only mechanical recycling at the end-of-life are 15-43% lower.

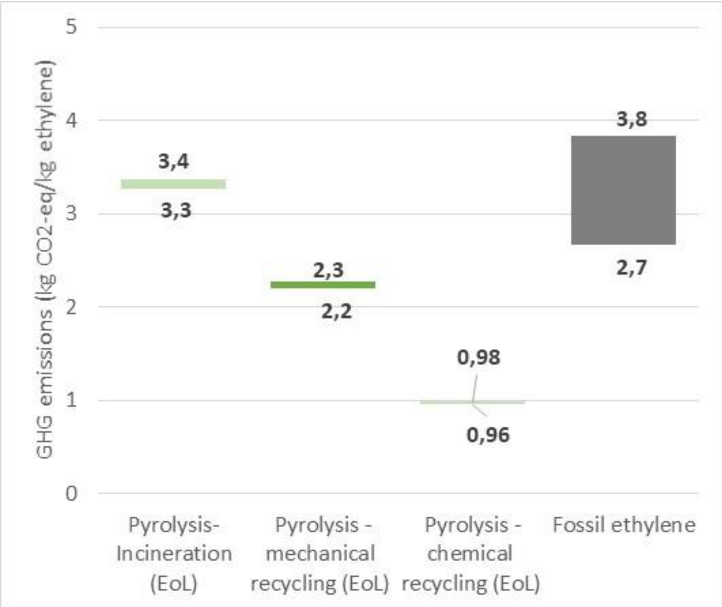

Figure 14. Comparison between the ranges of GHG emissions for plastic waste pyrolysis ethylene and fossil ethylene

Figure 15 shows the results of the different cases where end-of-life happens in the Netherlands and abroad. As mentioned earlier, a chain using recycling but ending in incineration would not offer significant savings. The cases with chemical and mechanical recycling combined as end-of-life (ChemRcy_NL and ChemRcy_EU) present the lowest life cycle GHG emissions factors (around 75% less than the fossil-fuel based reference cases). The difference is higher for the cases where the end-of-life takes place abroad. This can be explained by the higher electricity and heat substitution in the EU, compared to the Netherlands.

Literature shows larger emissions reduction potentials for chemical recycling via pyrolysis. This is due to the system boundaries set in those studies (see Appendix A). In other studies, the comparison is usually from the waste perspective and the pyrolysis of plastic waste is compared with other waste treatment options (e.g., incineration, refused derived fuel). In the product perspective, literature compares the production of plastic via pyrolysis with the fossil-fuel based reference and excludes end-of-life from the system boundaries. In this latter approach, the avoided incineration of the waste that is pyrolyzed is counted as credit to the recycling process and this is compared with the process emissions of plastics made from virgin oil. The assessment in this report follows the product perspective, however, the end-of-life step both for the pyrolysis value chain and for the fossil-fuel based references are included.

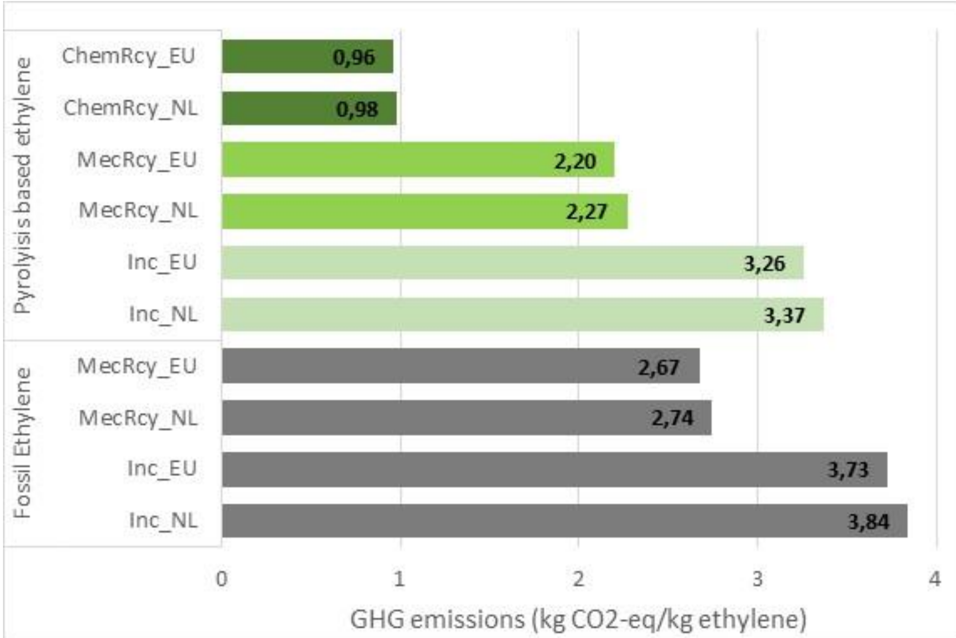

Figure 15. Life cycle GHG emissions for different end-of life options for ethylene production via pyrolysis of plastic waste and via fossil-fuel based references

5.2.2 *Geographical scope of emissions*

Figure 16 shows the distribution of emissions per region (in the Netherlands and abroad). In the case where incineration happens in the EU, around 27% of the total GHG emissions take place abroad. This share already considers the credits related to fossil ethylene substitution, and heat and electricity substitution. However, for the options MecRcy_EU and ChemRcy_EU, the end-of-life processes result in emissions credits abroad. Cases ChemRecy_EU and ChemRcy_NL present the highest GHG emissions credits among all cases, making them very relevant for the calculation of total emissions for these two cases. Therefore, when these credits remain in the EU (ChemRcy_EU), the emissions happening in the Netherlands for ChemRecy_EU are more than two-times higher than for ChemRcy_NL.

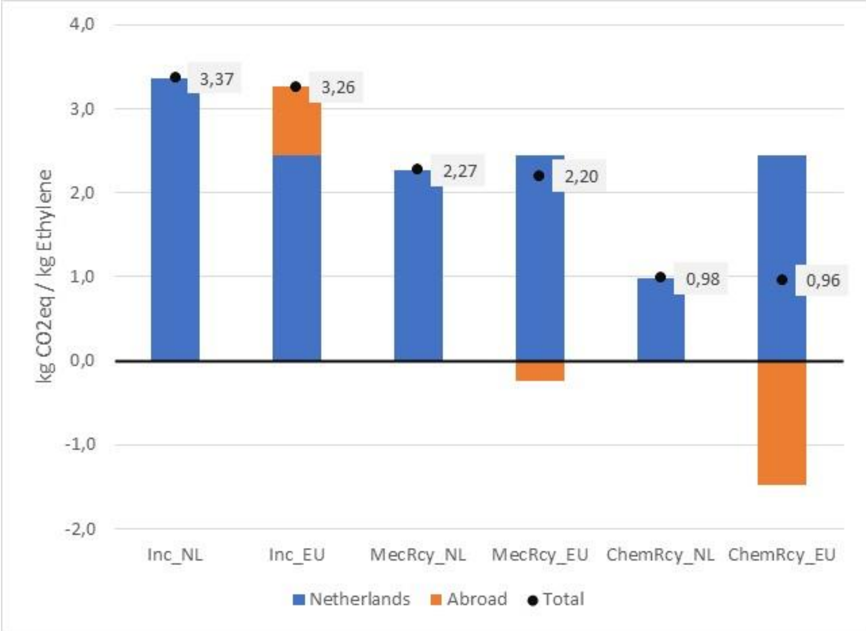

Figure 16. GHG emissions per region (Pyrolysis); all cases

Figure 17 shows the breakdown of the emissions amongst the cases where end-of-life happens outside the Netherlands. The comparison indicates that the credit related to substituting fossil ethylene with ethylene recovered from the recycling step is the main contributor to the reduction of the emissions abroad. Also, the total GHG emissions staying abroad are around six times lower for ChemRyc_EU when compared with MecRcy_EU, being the end-of-life emissions the main responsible for this difference.

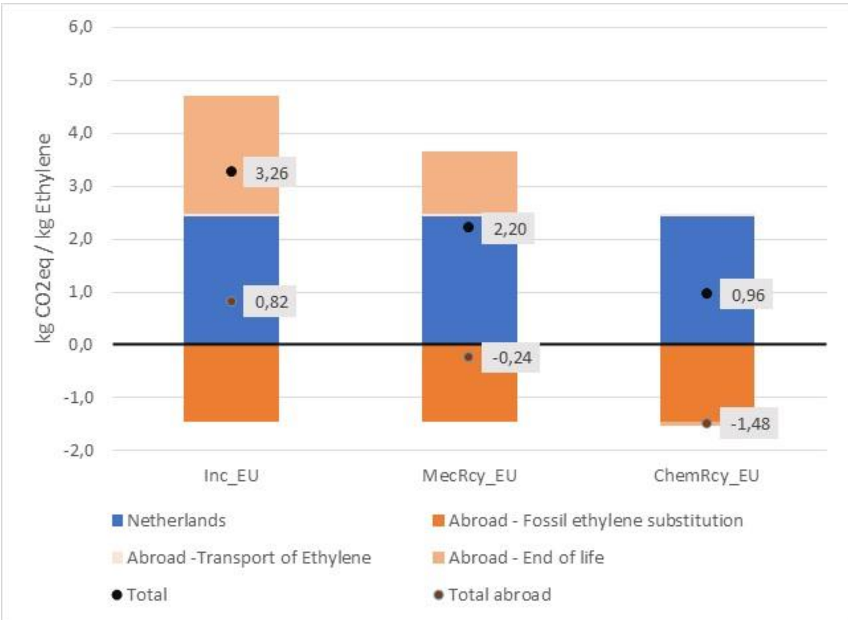

Figure 17. GHG emissions per region (Pyrolysis); cases with end-of-life abroad

5.2.3 *Emissions by scope and identification of hotspots*

In order to assess the main factors that influence the GHG emissions of the pyrolysis value chain, Figure 18 presents the detailed breakdown of activities that cause emissions. The end-of-life stage appears as the main contributor step to total GHG emissions for the cases that consider incineration as the end-of-life (Inc_NL and Inc_EU). For all other cases, the largest GHG emissions impact relates to the plastic waste conversion to pyrolysis process, representing more than 40% of the total emissions. This conversion process emits significant amounts of GHG emissions due to the combustion of the by-products for heat production, further details regarding this technology are present in Appendix B.

For all cases, *pyrolysis oil conversion to ethylene scope 1* has a higher contribution than *plastic waste sorting*. Transport steps and the emissions due to electricity and steam consumption during the pyrolysis oil conversion to ethylene (scope 2 emissions) have minimal impact for all cases. Regarding the contributors to the reduction of the total GHG emissions, *fossil ethylene substitution* is the main one in all cases. Although all cases present the same absolute value for the credit of fossil ethylene substitution, the end-of-life step also includes credits related to fossil product substitution for the cases with more than one recycling cycle. That is the main reason why the cases with chemical recycling combined with mechanical recycling at end-of-life (ChemRcy_NL and ChemRcy_EU) present negative values for the end-of-life emissions.

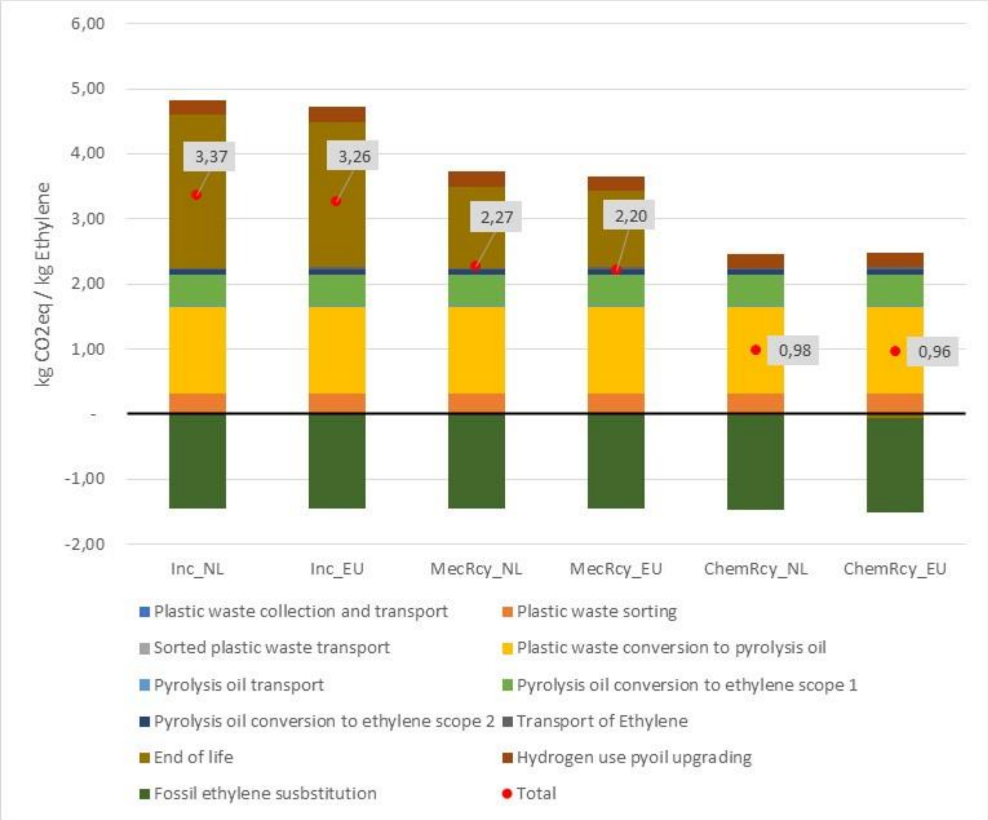

Figure 18. GHG emissions breakdown (Pyrolysis); all cases

Figure 19 illustrates further the emissions according to the different scopes. Scope 3 emissions consists of (i) scope 3 feedstock, covering all steps necessary to provide pyrolysis oil to steam crackers, from plastic waste sorting to pyrolysis oil production and transport, it also includes the production of hydrogen necessary for the oil purification; (ii) scope 3 end-of-life; and (iii) scope 3 material substitution, providing credit due to substitution of fossil ethylene. For all cases, scope 3 emissions have the largest contribution to the total GHG emissions.

In this case study, scope 3 emissions can be up to six-times higher than scope 1 emissions and up to 38 times higher than scope 2 emissions. It is important to mention that scope 1 and scope 2 emissions are the same for all cases because the activities related to these were assumed to be identical among the cases. The results presented in Figure 19 highlight the relevance of scope 3 emissions, as they contribute 42-84% of the total emissions of the value chains present in the picture.

For the cases with incineration (Inc_NL and Inc_EU), scope 3 end-of-life emissions play an important role and are the highest compared to the other cases considering recycling as end-of-life. This occurs mainly because these cases represent linear value chains, which means that the carbon that was initially embedded in the recycled plastic is released to the atmosphere in the form of CO_2 at the end-of-life. In contrast, scope 3 feedstock emissions are the main contributors for the cases that present recycling as end-of-life option (MecRcy_NL, MecRcy_EU, ChemRcy_NL and ChemRcy_EU). An important fraction of carbon is not released to the atmosphere in those cases and can stay for a longer period of time inside the system boundary, which reduced end-of-life emissions, compared to incineration. For the cases ChemRcy_NL and ChemRcy_EU, scope 3 end-of-life emissions can even reach negative values, mainly because the end-of-life is a combination of chemical and mechanical recycling techniques and more carbon is kept within the system boundary.

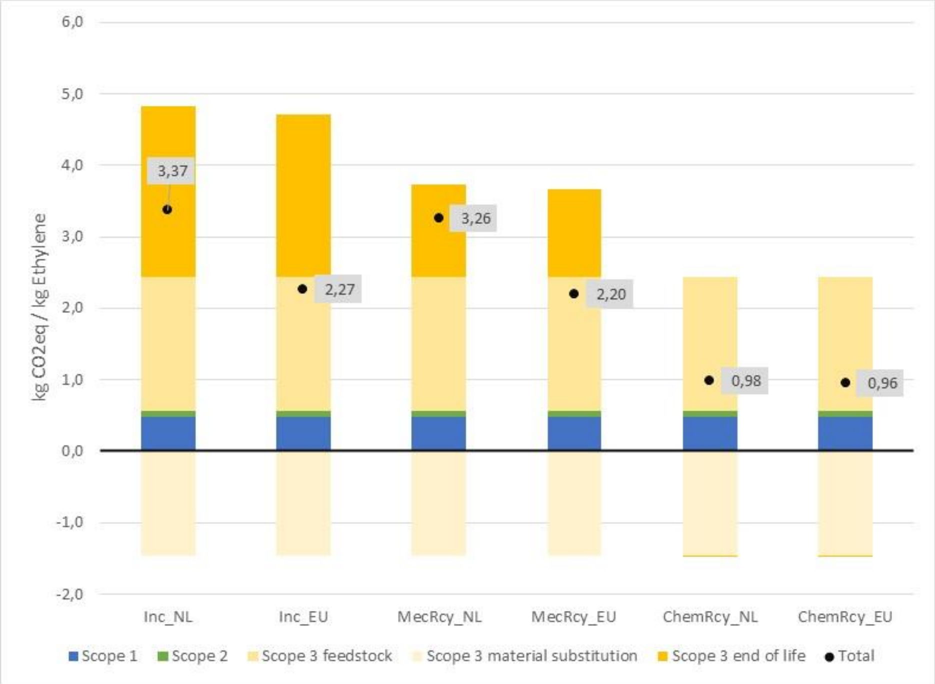

Figure 19. GHG emissions per scope (Pyrolysis); all cases

5.2.4 *2030 Scenario*

A future scenario for 2030 is also included in this study. This scenario focuses on reducing scope 3 feedstock emissions and proposes significant changes to the activities related to feedstock supply. The following aspects construct the future scenario:

i. Plastic waste sorting losses are reduced to 5% (an improvement from the original value of 10%). This reduces the incineration of material losses
ii. Plastic waste conversion to pyrolysis oil material efficiency is increased to a level where the char and residual gas by-products are enough to only meet the heat demand from the pyrolysis reaction. Therefore, no extra heat is exported and less combustion emissions occur (around 74% less)
iii. Hydrogen use in the purification of pyrolysis oil is assumed to be green hydrogen
iv. Electricity grid in the NL presents lower emission factor, in line with the projections from the KEV 2020 for 2030 (PBL, 2020).

Only cases that occur entirely in the Netherlands and present recycling as end-of-life option are evaluated in the future scenario. The results, in comparison to the base configurations, are presented in Figure 20. The results show that the total emissions for the future scenario are almost halved for the case with mechanical recycling in 2030, when compared with the current framework. In case of continued chemical recycling (ChemRcy_NL-2030) the life cycle GHG emissions become even negative in 2030.

For both future cases, the emissions from the sorting step are 41% lower and the emissions from the plastic waste pyrolysis process are 82% lower, when compared to the current cases. The total emissions reduction relates mainly to the material efficiency increases in the overall life cycle due to the assumed improvements in the pyrolysis oil production process and in sorting. Therefore, more carbon is kept within the system boundaries, when compared to the baseline. Although scope 2 emissions reduce by 74% in both future cases, their impact is minimal to the total GHG emissions value because the scope 2 emissions from the current cases already represents a small fraction of the total.

Other relevant point is the fact that the improvement of the material efficiency allows the case ChemRcy_NL to reach a negative GHG emissions as carbon is circulated back into the system and leakages are much lower compared to the baseline (current).

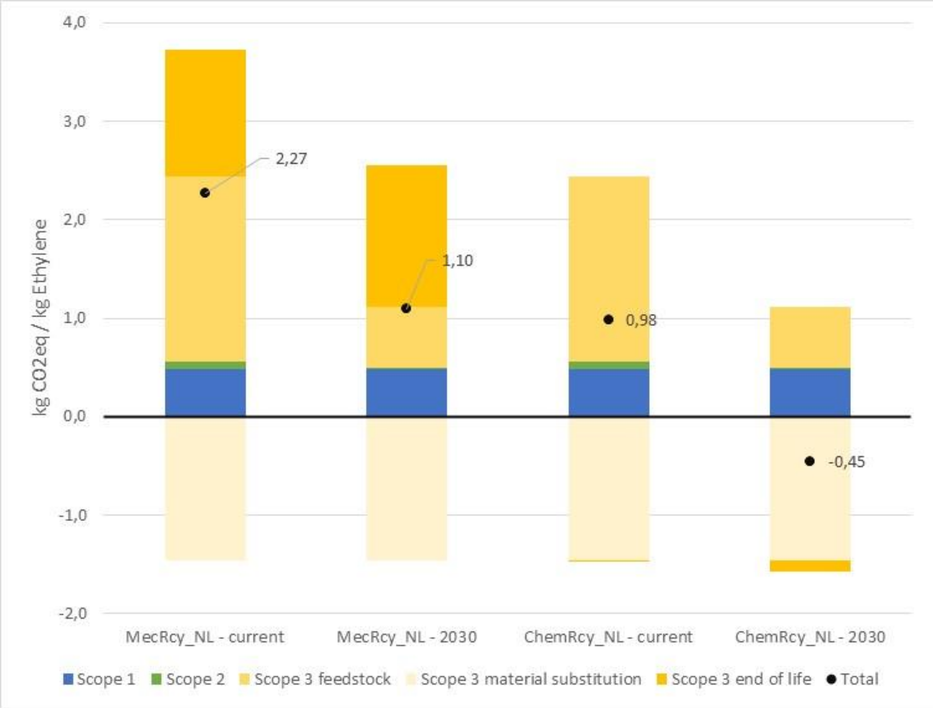

Figure 20. GHG emissions per scope 2030 scenario (Includes cases which only occur in the Netherlands)

6 Use of this approach and the calculations to further support policy instruments

Renewable energy supply in the Netherlands has been supported through Stimulation of Sustainable Energy Production and Climate Transition Scheme (SDE++), which is an operating subsidy provided to energy producers during the operation period of a project (PBL, 2021b). SDE++ has been expanded from renewable energy supply to supporting other carbon-reducing technologies. Within the broadening of SDE++, production of biobased ethylene and chemical recycling of plastics (PS solvolysis and PET dissolution) are considered. An important aspect of the SDE++ is the calculation of subsidy intensity, which is based on the production cost and the GHG emissions reduction potential. While the emissions reduction potential is based on the scope 1 and 2 emissions, this may need to be adapted for the tradable commodities, like production of biobased bulk chemicals. The approach introduced in this report can be a useful tool to calculate total emission reduction for a number of different options, where scope 3 emissions savings from a project are reflected.

Another existing policy instrument that supports the innovations in industry is the DEI+ (Demonstratie Energie-en Klimaatinnovatie) investment subsidy. Circular economy is among the topics included in this instrument, where plastic recycling and biobased raw materials that replace raw materials from fossil and mineral origin fall under. This subsidy is meant for demonstration plants that lead to CO_2 reduction in the Netherlands. For upscaling technologies with higher technology readiness level (TRL), new instruments are being discussed, such as the National Investment Scheme for Industry Climate Projects (NIKI). This subsidy programme will be comparable to the EU innovation Fund. Currently the outline of such a scheme is being examined. The intent of this scheme is to provide an open and flexible subsidy facilitating large complex breakthrough technologies for e.g., to facilitate green fertilizer, plastic and steel production. One of the application criteria for the EU Innovation Fund is the avoidance of GHG emissions. Such a criterion is also likely to be needed for the projects to be implemented in the Netherlands under NIKI. The proposed approach in this study can support this process by providing insights on the life cycle GHG emissions and emission savings potentials, where scope 3 emissions are explicitly calculated.

As the results show in chapter 5, scope 3 emissions from the chemical industry perspective relate to the feedstock supply and end-of life stages. In the case of biobased products, feedstock supply related emissions could to some extent be addressed in a certification scheme, where cradle-to-gate emissions are reported, and only the supply chains that do not exceed a certain emission threshold can be allowed for the production of biobased chemicals. For the chemical recycling options also a certification of waste flows can help controlling the GHG emissions, especially when they are imported. Furthermore, depending on the scale of the chemical recycling, i.e. pyrolysis, this step may fall under the EU ETS.

When it comes to the end-of-life related scope 3 emissions, these are more complex as biobased and circular options result in emission savings, when compared with the fossil-fuel based references, and when this happens abroad they cannot be counted towards the national GHG emissions reduction targets.

Establishing EU-wide targets or obligations for the use of renewable raw materials and recycled materials, for instance with a quota for renewable and circular carbon in “drop in” products in the chemical and plastics industries (Nova, 2021; Trinomics, 2021) can create a market for renewable and circular products in Europe and will have major impacts to end-of-life emissions. The market demand for renewable and circular carbon can be supplemented by a systematic expansion of recycling in Europe (Nova, 20X). The Netherlands already has targets in this area under the national waste management plan, whereby the proportion of preparation for reuse and recycling of industrial waste must be at least 85% by 2023. The Waste Framework Directive (WFD) makes it possible to introduce such an EU target. This will help reducing scope 3 emissions related to the-end-of life. Such instruments, nevertheless, will not avoid any possible scope 3 emissions occurring outside of the EU.

Product related polices, for instance Ecodesign Directive may in the future also include requirements on lifetime conditions, material efficiencies, material composition choices and their recyclability.

7 Discussion and conclusions

7.1 Discussions

Chemical recycling (pyrolysis) and mechanical recycling

In this study, chemical recycling is considered to complement mechanical recycling. Thus the case represented as continues chemical recycling introduces an end-of life where both mechanical and chemical recycling co-exist. It was assumed that the mono-plastic streams would be treated via mechanical recycling and the mixed material streams would be directed to pyrolysis. Not all plastics can be mechanically recycled, and plastic waste that reaches recycling facilities is often contaminated or mixed. This hinders mechanical recycling rates and results in large quantities of plastics being incinerated. The mechanical recycling rate was kept to 42% of the total plastic waste, which is the current collection rate for mechanical recycling. The rest of the mixed waste was assumed to be processed via pyrolysis. The material losses from collection and sorting steps were assumed to be incinerated. Thus, the lower GHG emission performance of the mechanical recycling relates to lower recycling rates and, therefore, larger waste stream that needs to be incinerated. For this reason, the results should not be interpreted as chemical recycling performing much better than mechanical recycling. It mainly shows that the combination of chemical recycling and mechanical recycling at the end-of-life performs better than only mechanical recycling, where a large amount of mechanically not recyclable plastic waste goes to incineration.

Land use change (LUC) issues surrounding biobased options

This study did not include the emissions related to direct and indirect land use change (dLUC and iLUC), which have been at the centre of a scientific debate for a very long time. dLUC refers to the changes where the land use for product under assessment takes place. In this study, this refers to direct impacts of sugarcane cultivation on land. iLUC refers to a possible shift in land use due to increased demand for the product. When arable land that is already in use for activities such as cropping or grazing, may be used to produce sugar cane ethanol because of increased demand to produce bioethylene in our case. This increase may result in the expansion of agricultural land at the expense of forest or grassland, or through intensification of products, or the displacement of crops (Tonini et al., 2021). Such effects are captured using different models in literature. These studies provide different results, which makes it exceedingly difficult to include LUC effects into the life cycle GHG emissions calculations. Such possible effects are better to be included through sensitivity analysis as presented in this report where the effect of increase of emissions from sugarcane was assessed.

Dynamic accounting and temporal storage of biogenic C

Another important discussion point within the LCA of biobased products is the dynamic accounting of the biogenic carbon cycle and the temporary storage within the technosphere. This study followed the carbon-neutrality approach, which has been criticised as this approach may provide misleading results, depending on the feedstock type. Nevertheless, annual crops, such as sugar cane, are considered to have a net-zero impact on the climate as annual crops will re-sequester harvested CO_2 every year. However, other biomass types, with longer growth period may have short term climate-impacts and these may become essential to inform decisions on a temporal scale (Tonini et al., 2021).Thus, further research and a particular attention to the biomass harvesting and the growth period and related to that, the GHG emissions impacts is needed.

7.2 Conclusions

7.2.1 Main goals of the calculation approach introduced in this study

This study introduces a practical and harmonised approach, based on life cycle assessment principles, to provide insights into the GHG emissions effects of circularity measures and biobased substitution options. This approach enables a consistent and fair assessment of different technologies. It not only enables the calculations of emissions that happen in different steps of the value chain, but also categorises them as scope 1, 2 and 3 based on the GHG Protocol. These emissions can be further presented as occurring within the national borders or outside of them in order to show the possible upstream and downstream emission consequences of an industrial activity in the Netherlands. The approach also identifies which steps of the value chain contribute to life cycle emissions the most, thus highlighting hotspots which can be targeted for the implementation of technologies to maximise emission reductions in the long term. The method also allows for assessing prospective scenarios and identifying under which conditions emissions decrease over time.

The approach presented here is not meant to reflect the exact emissions of innovative technologies in the Netherlands. In fact, such implementation-based emissions should be calculated by the companies themselves using the company specific datasets. Instead, this approach aims to present a more generic default value, which can be a good basis for policy making.

7.2.2 Interpretation of the results

Two case studies, the production of ethylene from biomass and from plastics pyrolysis oil, were used to illustrate how this approach can be implemented.

Case study results indicate that both biobased ethylene production from sugar case and the production of ethylene via pyrolysis oil result in GHG emissions savings when these value chains are compared with the fossil-fuel based references. For the biobased value chains the emission reductions are in the range of 77-90%. These are 63-75% for the pyrolysis oil value chain with chemical recycling combined with mechanical recycling as the end-of-life, and between 15-43% when the end-of-life is mechanical recycling. It is important to note that results can vary widely depending on the datasets used and assumptions made. Sensitivity analysis showed that there are critical parameters that can change results dramatically, for instance by increasing emissions related to biomass production by 100%, the total value chain emissions doubles. Nevertheless, compared to fossil ethylene, important savings can still be achieved. In the case of ethylene from pyrolysis oil, the future scenario shows that life cycle GHG emissions can even reach a negative value if the process material efficiency improves, and the electricity grid becomes greener.

It is necessary to highlight that these results are case specific, therefore it would be misleading to extrapolate these results to all possible biobased options. More configurations with, for instance, different feedstock types and supply options will be needed. The same applies to recycled plastics, as the characteristics of the plastic waste blend can significantly change from case to case.

7.2.3 Scope emissions according to this study

Existing national policies are designed to reduce emissions from industry within the Dutch borders and there are good reasons for that. However, when it comes to the production of tradable goods, there is no certainty that these goods will also be consumed in the Netherlands. In fact, a large amount of the produced ethylene in the petrochemical industry is exported. This will mean that a significant amount of biobased or circular ethylene will be exported to other countries and consumed there, resulting in emission savings occurring elsewhere. Next to that, feedstocks, particularly in case of biobased products, will be produced and supplied from outside of the Netherlands and related emissions will occur elsewhere. Such emissions will be the scope 3 emissions from the petrochemical industry perspective and the existing polices do not focus on these emissions.
The results indicate that, indeed, the majority of emissions from the industrial processes studied can be grouped as scope 3 emissions. Within the scope 3 activities, emissions related to biomass feedstock production and harvesting, and transportation of biomass feedstocks and intermediates contribute most to scope 3 emissions. The production of biobased ethylene in the Netherlands will increase demand for biomass feedstocks and intermediates abroad. This will also increase the amount of goods transported into the Netherlands. Even though the supply related emissions will fall under the policy framework of the respective country, the policy instruments in the Netherlands can be designed in a way to incentivise life cycle GHG emissions improvements. Introduction of a minimum emissions reduction criterion or a maximum total emissions threshold based on the life cycle GHG emissions as a prerequisite can help achieve this. Such a criterion would, however, have to be part of a certification scheme like that which has been implemented for the biofuels for transport sector.

The end-of-life also plays an important role and depending on where this takes place, emission savings may happen in the Netherlands or abroad. While emission savings that happen outside the Netherlands cannot be counted towards the Dutch emissions reduction goals, this should not be a reason to disincentivise such value chains as the climate change is a global issue.

Among the different activities, feedstock supply that covers collecting and sorting of waste plastics and their conversion to pyrolysis oil, produce the largest GHG emissions. This is no surprise as pyrolysis is an energy-intensive process. This process is assumed to be undertaken in the Netherlands, and it is not clear whether all processing will fall under the EU-ETS as this will depend on the scale of the plant. Next to that, even though this process is energy intensive, as a circular production option, it avoids the use of virgin materials, which increases emissions credits related to material substitution after each recycling cycle. Also, this technology can handle waste streams that are currently difficult to recycle, such as DKR-350.

Key take home messages on the work presented in this study are as follows:

- The approach presented in this report (which is based on the LCA principles), can be adopted and applied to potential value chains to assess the impacts of scope 1, 2 and 3 emissions.
- Indirect scope 3 emissions can be substantial and even be the major part of life cycle emissions compared to scope 1 and 2 emissions.
- Results show that there are important differences in emissions happening in the Netherlands or abroad. As industry is currently in transition and expected to adopt structural technology changes at plant level, this can result in completely different upstream and downstream routes to the existing ones. This will therefore have a large influence on potential emission savings when looking into relevant value chains for transforming industry.
- Results of the case studies showed that end-of-life treatment is a key value chain step and depending on which technologies are adopted for that purpose, emission savings can be highly impacted. Even in alternative production chains, recycling of material is key to increase emissions savings when compared to conventional systems.
- Since climate change is a global problem, policy instruments should at least aim to not have counterproductive effects in scope 3. This can only be guaranteed if structural instruments covering life cycle emissions are used (e.g. such as a carbon tax) instead of just scope 1 emissions at plant or company level.
- A dynamic tool should be developed to analyse and assess life cycle emissions in different systems at different time horizons.

References

Boulamanti, A., & Moya, J. A. (2017). Energy efficiency and GHG emissions: Prospective scenarios for the Chemical and Petrochemical Industry. In *European Union*. https://doi.org/10.2760/20486

Ecoinvent. (2020). Ecoinvent Database v3.3. *Www.Ecoinvent.Ch.*

FAO. (2020). *BEFS RA. Energy end-use options*. *Available*.

Fivga, A., & Dimitriou, I. (2018). Pyrolysis of plastic waste for production of heavy fuel substitute: A techno-economic assessment. *Energy*, *149*, 865–874. https://doi.org/10.1016/j.energy.2018.02.094

ISO. (2006). *ISO 14044:2006. Environmental management -- Life cycle assessment -- Requirements and guideline*.

Jeswani, H., Krüger, C., Russ, M., Horlacher, M., Antony, F., Hann, S., & Azapagic, A. (2021). Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery. *Science of the Total Environment*, *769*. https://doi.org/10.1016/j.scitotenv.2020.144483

Mohsenzadeh, A., Zamani, A., & Taherzadeh, M. J. (2017). Bioethylene Production from Ethanol: A Review and Techno-economical Evaluation. *ChemBioEng Reviews*, *4*(2), 75–91. https://doi.org/10.1002/CBEN.201600025

PBL. (2020). *Klimaat- en Energieverkenning 2020* (p. 184). Planbureau voor de Leefomgeving.

PBL. (2021a). Klimaat en Energieverkenning 2021. KEV. *Available at: Https://Www.Pbl.Nl/Sites/Default/Files/Downloads/Pbl-2021-Klimaat-En-Energieverkenning-2021-4681.Pdf*.

PBL. (2021b). Stimuleringsregeling Duurzame Energieproductie en Klimaattransitie (SDE++). *Available at: Https://Www.Pbl.Nl/Sde*.

Picuno, C., Van Eygen, E., Brouwer, M. T., Kuchta, K., & van Velzen, E. U. T. (2021). Factors shaping the recycling systems for plastic packaging waste—a comparison between austria, germany and the netherlands. *Sustainability (Switzerland)*, *13*(12). https://doi.org/10.3390/su13126772

TNO. (2018). *De transitie van Nederland naar een circulaire economie. Effecten van het Rijksbrede Programma Circulaire Economie en de Transitieagenda's op de emissie van broeikasgassen*.

Tonini, D., Schrijvers, D., Nessi, S., Garcia-Gutierrez, P., & Giuntoli, J. (2021). Carbon footprint of plastic from biomass and recycled feedstock: methodological insights. *International Journal of Life Cycle Assessment*, *26*(2), 221–237. https://doi.org/10.1007/S11367-020-01853-2/TABLES/3

Tsiropoulos, I., Faaij, A. P. C., Seabra, J. E. A., Lundquist, L., Schenker, U., Briois, J. F., & Patel, M. K. (2014). Life cycle assessment of sugarcane ethanol production in India in comparison to Brazil. *International Journal of Life Cycle Assessment*, *19*(5), 1049–1067. https://doi.org/10.1007/s11367-014-0714-5

Uslu, A., Moncada, J., & Oliveira, C. (2021). Demand for Renewable Hydrocarbons in 2030 and 2050. *TNO Report*, *available*.

Zuurbier, P., & van de Vooren, J. (2008). Sugarcane Ethanol. Contributions to climate change mitigation and the environment. *Wageningen Academic Publisher*, *The Netherlands*.

A Literature review

This Appendix As the literature review which is the basis for Chapter 2. The report presenting the literature review is GHG emissions of circular and biobased innovations in industry- a literature review. The report is appended as a separate document.

Appendix C presents details of mass and energy flows used to estimate emissions of the value chains assessed in this study. Data to calculate those mass and energy flows is presented in Appendix B. The data is appended as a separate appendix to this report.

B Assumptions and description of steps included with the system boundaries of the case studies

This appendix presents assumptions and a detailed description of the steps included within the system boundaries of the case studies selected.

B.1 Ethylene production from sugarcane

This section includes a description of the steps presented in **Error! Reference source not found.** for ethylene production from sugarcane.

Feedstock production
This step considers the growing and harvesting of sugarcane in Brazil. Data regarding emissions from sugarcane growing and harvesting was gathered directly from ecoinvent V3.3 databases (Ecoinvent, 2020). Direct and indirect land use change effects were excluded from the analysis. In this step, 3% loss of dry matter was assumed between the harvesting and distribution step. The amount of sugarcane needed was estimated by using the ethanol to ethylene conversion yield , and thus estimating the amount of sugarcane required to produce ethanol and then its conversion to produce 1 kg of ethylene (functional unit).

Feedstock transport
Transport of sugarcane to the ethanol production process was considered here. In general, ethanol production processes are located close to sugarcane plantations in Brazil. In this case, transport was assumed to be 50 km in distance, in medium size trucks (based on (Zuurbier & van de Vooren, 2008)).

Auxiliary raw materials production
Emissions related to auxiliary inputs for ethanol production were accounted for. Inputs include lime, sulfuric acid, organic chemical (for fermentation), water, and yeast. Emission factors for this inputs were directly gathered from ecoinvent databases (Ecoinvent, 2020). Inventory data for ethanol production yields and inputs was gathered from (Tsiropoulos et al., 2014) and completed from the mass and energy balances provided in the BEFS RA tools published by FAO (FAO, 2020).

Ethanol production (intermediate production)
Ethanol production from sugarcane comprises the conversion of sugars into ethanol and CO_2 by fermentation. The process of producing ethanol also produces sugarcane bagasse as co-product which is used for electricity production and a fraction for heat purposes. The electricity produced in the process offers a GHG emissions credit as it was assumed that it replaces electricity from the grid. Also, the fraction of sugarcane bagasse produced was assumed to replace 30% of the heat capacity of natural gas. This is a conservative assumption to avoid giving high heating value and market to sugarcane bagasse. In this process, the export of sugarcane bagasse also provides a credit on GHG emissions in the ethanol production process. 1 kg of ethanol is produced per about 15 kg of sugarcane, and about 1.1 kg of CO_2 per kg of ethanol is produced. CO_2 from fermentation and from

burning sugarcane is accounted here as biogenic. Inventory data was gathered from (FAO, 2020; Tsiropoulos et al., 2014)

Ethanol transport

As it is assumed that ethylene is to be produced in the Netherlands, and there is the need to import ethanol from Brazil. In this case, it was assumed that ethanol was transported in tank trucks from the distilleries to the port of Santos, with an average distance of 300 km. Ethanol was shipped to the port of Rotterdam on a 60,000 DWT (Deadweight tonnage) ship. The distance between both ports is 12,497 km. The transport from the terminal to the ethylene production in the Netherlands was assumed to be undertaken by truck and for a distance of 25 km. It is important to mention that transport is included in the analysis as the value chain of ethanol to ethylene does not follow an identical transport pathway as conventional ethylene production from naphtha (see section 4.3), as naphtha or oil is not imported from Brazil to the Netherlands. This route was selected as example in the analysis, but the user should be aware that logistics tend to change over time, the analysis looks to understand which parameters affect the assessment the most and in case long distance transport is a dominant factor, effect on distances and therefore routes are considered.

Ethylene production

The ethylene production step consists of the catalytic conversion of ethanol into ethylene. This process requires electricity and natural gas (scope 2) as energy inputs. Natural gas scope 2 emissions are those related to the extraction and supply of natural gas into the processing facility. Then natural gas is used as fuel for the furnace where the reaction takes place. The burning of natural gas leads to direct emissions in the processing facility, which are classified as scope 1 emissions. In general, 0.44 kg of ethylene are obtained per every kg of ethanol fed into the process. Electricity consumption is 0.36 MJ per kg of ethanol, and natural gas 0.75 MJ per kg of ethanol. The inventory data of this process was gathered from (Uslu et al., 2021).

Ethylene transport

Ethylene was assumed to be transported in trucks and to be consumed and treated (end-of-life) in the Netherlands and in Europe. Transport distance within the Netherlands was assumed as 100 km while transport within Europe as 1000 km.

End-of-life options

For this value chain two end-of-life options were considered. The system assumes that ethylene ends up in the form of plastic and two alternatives for treatment were included. Incineration and chemical recycling. As there is high uncertainty on were end-of-life is happening, the analysis was undertaken as if it would happen both in the Netherlands and outside the Netherlands. Below explanation of the end-of-life options.

Incineration

Incineration considers burning the ethylene based plastic, resulting in the conversion of the carbon embedded in the plastic into CO_2. Incineration can be carried out with or without energy recovery, but if used, the energy released during combustion is used to produce heat and power. Heat and power are here obtained as co-products of the incineration process and account for credits in CO_2 accounting.

Mechanical recycling
Mechanical recycling considers collecting and sorting plastic based ethylene. A collection rate of 42% was considered (Picuno et al., 2021). The plastic that is collected undergoes a selection process which yields 71% of the collected plastic. This means that 30% of the produced ethylene is mechanically recycled. The rejected plastic, and no collected plastic was assumed to be incinerated and heat and power were also produced.

B.2 Ethylene production from plastic waste pyrolysis

Collection and sorting (feedstock supply)
Mixed household packaging plastic waste is assumed as the feedstock of this value chain. No specific composition was considered; however, it is expected that this stream will be rich in polyethylene, polypropylene and polystyrene.

The transport of the collected waste to the sorting facility presents material losses of 1% and the distance assumed between the collection and the sorting facility was 100 km. The plastic waste sorting was assumed to focus on polyethylene, polypropylene and polystyrene, and around 10% of material losses was considered, based on (Jeswani et al., 2021). Therefore, around 89% of the total input is sorted out as the pyrolysis feed. This process includes electricity consumption (250 MJ/t MPW). The transport of the sorted plastic waste to the pyrolysis plant also presents material losses of 1% and the distance assumed between these two locations is 50 km. These material losses are considered to be the incinerated at some point and the emissions and credits related to this process are included (further details on incineration are explored in the end-of-life section).

Pyrolysis oil production
The mixed plastic waste is submitted to high temperature under controlled conditions to allow the pyrolysis reactions. The pyrolysis results in three main material flows: residual gas, pyrolysis oil and solid char. Literature indicates a material efficiency of around 85.8%wt towards the pyrolysis oil (Fivga & Dimitriou, 2018). Both by-products are assumed to be incinerated, providing heat to the pyrolysis reactor. The heat produced is considered by Fviga & Dimitriou (2018) to be more than sufficient to meet the internal demand, allowing export of residual heat.

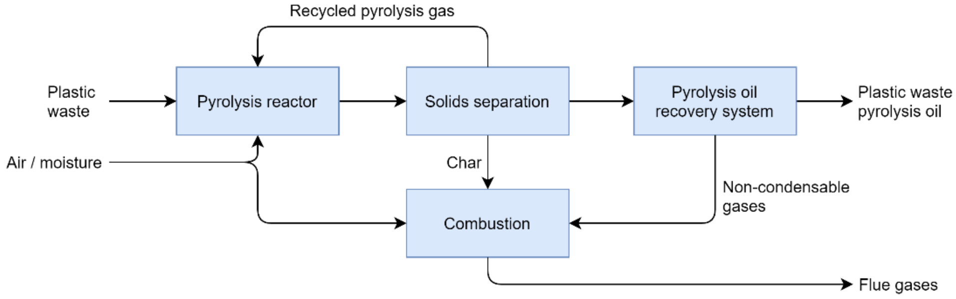

Figure 21 Plastic waste pyrolysis process in details

Following the system expansion approach, the credit for the residual heat production is also considered.

Pyrolysis oil purification
The pyrolysis oil may contain contaminants and heavy components (up to C30 hydrocarbons), therefore an upgrading process is considered in the value chain to adjust the oil quality to typical steam cracker feed. The steam cracker facilities in the Netherlands usually use naphtha and gasoil as fossil feedstock, however, there is scarce literature on the quality that this pyrolysis oil should reach to be suitable as a substitute. Nonetheless, it is expected that hydrotreating technologies that are already present in the market will be sufficient for this type of upgrade. It is considered that the pyrolysis oil passes through catalytic hydrocracking, which converts heavy molecules into lighter unsaturated hydrocarbons. The pyrolysis oil composition presented by Fviga & Dimitriou (2018) indicates that it might have similar carbon distribution as vacuum gas oil, a typical fossil feedstock for hydrocracking processes in refineries. For this reason, the material efficiency assumed is based on the vacuum gasoil conversion to naphtha and diesel, which is around 97.5%wt (Meyers, 2004).

Hydrogen is needed for this treatment, and the consumption is around 2.5% wt (feedstock based) for typical hydrocrackers. This f hydrogen is considered to be obtained via conventional process (steam methane reformer) and the related emissions are included.

Ethylene production
The ethylene production step is based on the conventional steam cracking process in which naphtha is submitted to high temperature and converted to several petrochemical products (such as ethylene, propylene, butadiene, benzene, etc). The material yields and energy requirements for this technology are based on average values regarding naphtha crackers in Europe (Boulamanti & Moya, 2017). The material efficiency towards ethylene is around 31%wt. Because a large set of products is obtained at a steam cracker, mass allocation approach is applied to determine the CO_2 emissions related to the ethylene production. Also, the credit for fossil ethylene substitution is included.

B.3 End-of-life options

Incineration
As indicated by Figure *22*, the incineration process can deliver electricity and heat, therefore, the credits for these energy flows are included in the assessment. The direct CO_2 emissions from incineration are accounted and these are based on the CO_2 released from ethylene combustion because the end-of-life of only ethylene-based plastics are included.

Mechanical recycling
In 2017, the Netherlands collected around 42% of post-consumed household packing plastic to be mechanically recycled (Picuno et al., 2021). This rate is used to estimate how much of the ethylene-based plastic from the value chain would be available for mechanical recycling. Literature estimates that the process can reach a material efficiency of 71%wt, which results in an overall recycling rate of 30%wt.

The waste that cannot be recycle via this method is incinerated. No distinction about the plastic quality is made in this study, therefore, the resulted recycled material is assumed to substitute 100% fossil ethylene.

Chemical recycling (pyrolysis) and mechanical recycling
It is more realistic that both mechanical recycling and chemical recycling options would co-exist, situation in which mono-plastic streams would be treated via mechanical recycling and the mixed material streams would be directed to pyrolysis. For this end-of-life alternative, the current collection rate for mechanical recycling is kept (42%) and the rest is processed via pyrolysis. Incineration takes place to address the material losses from collection and sorting steps in both methods.

Figure *22* illustrates these options, together with the respective final products.

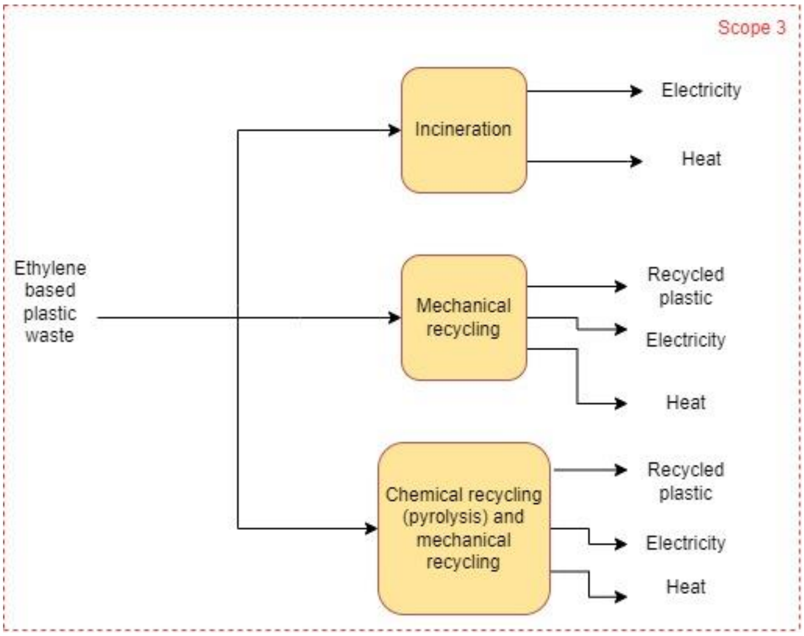

Figure *22* End-of-life options for the plastic waste pyrolysis value chain

Table *1* - Summary of the end-of-life characteristics

End-of-life option	Incineration	Mechanical recycling	Chemical (pyrolysis) and mechanical recycling combined
Usable share	100%	42%	100%
Credit to ethylene substitution	No	Yes	Yes
Credit to heat substitution	Yes	Yes	Yes
Credit to electricity substitution	Yes	Yes	Yes
Overall recycling rate towards ethylene based plastic[5]	0%	30%	44%

[5] The calculation of overall recycling rate takes into account the material losses from collection and sorting.

Conventional ethylene production

Data for emissions related to ethylene production from steam cracking of naphtha was directly collected from ecoinvent V3.7 databases (Ecoinvent, 2020). Data extracted from ecoinvent considers the cradle to gate emissions of ethylene production in Europe, where naphtha is the most used feedstock. This means that emissions related to the production of naphtha, transport of naphtha to crackers and conversion of naphtha into olefins are included. End-of-life emissions related to conventional ethylene are estimated using same datasets are those for the two case studies cited in this study.

As the process to produce ethylene is a multiproduct process and other streams such as propylene, butadiene, benzene, among others, are produced, ecoinvent V3.7 databases considers mass allocation to ethylene. This means that emissions of the steam cracking process are allocated between the co-products. Thus, emissions of fossil ethylene presented in this study only correspond to the contribution of ethylene in the process. The fossil reference is based on the aggregation of the cradle to gate emissions (1.45 kg CO_2 eq/kg ethylene) plus the estimated emissions for each end-of-life option.

C Mass and energy flows used to estimate emissions of value chains

Appendix C presents details of mass and energy flows used to estimate emissions of the value chains assessed in this study. Data to calculate those mass and energy flows is presented in Appendix B. The data is included as a separate appendix to this report.