SWEDISH LIFE CYCLE CENTER

Impacts on fuel producers and costumers of conflicting rules for life cycle assessment

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IMPACTS ON FUEL PRODUCERS AND CUSTOMERS OF CONFLICTING RULES FOR LIFE CYCLE ASSESSMENT

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THE SWEDISH KNOWLEDGE CENTRE FOR RENEWABLE TRANSPORTATION FUELS

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PREFACE

This project has been carried out within the collaborative research program *Renewable transportation fuels and systems* (Förnybara drivmedel och system), Project no. 50481-1. The project has been financed by the Swedish Energy Agency and f3 – Swedish Knowledge Centre for Renewable Transportation Fuels.

The Swedish Energy Agency is a government agency subordinate to the Ministry of Infrastructure. The Swedish Energy Agency is leading the energy transition into a modern and sustainable, fossil free welfare society and supports research on renewable energy sources, the energy system, and future transportation fuels production and use.

f3 Swedish Knowledge Centre for Renewable Transportation Fuels is a networking organization which focuses on development of environmentally, economically and socially sustainable renewable fuels. The f3 centre is financed jointly by the centre partners and the region of Västra Götaland. Chalmers Industriteknik functions as the host of the f3 organization (see https://f3centre.se/en/about-f3/).

The ICON project has been conducted in collaboration with multiple actors including universities, research institutes, the vehicle and fuel industry in Sweden and more. The reference group of the project consisted of representatives (in alphabetical order) from: Air Liquide (FordonsGas), BASF - The Chemical company, Drivkraft Sverige, Lantmännen Aspen, Network for Transport Measures (NTM), Nouryon, Preem AB, Scandinavian Enviro Systems AB, Scania, SEKAB, ST1 AB and Volvo Group.

This project has been coordinated within Swedish Life Cycle Center, a national competence center for credible and applied life cycle thinking in industry and society. (More information: https://www.lifecyclecenter.se/)

During the final phase of the project, two participants changed employers. Anna Ekman Nilsson, formerly RISE, is now employed at Skånemejerier and Jennifer Davis, formerly RISE, is now employed at Volvo Cars.

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SUMMARY

The use of life cycle assessment (LCA) as a tool for estimating the environmental performance of a product or service in a holistic and systematic manner is increasing. Fuel producers may need to apply different methodological frameworks to be used in different contexts; internally for product development activities as well as externally for communication with customers or authorities. Different LCA frameworks may vary in scope, system boundaries (i.e. life cycle stages to be considered) or modelling requirements (such as data demands but also more detailed methodological features). They may also vary in terms of information they can provide in relation to the environmental performance of the product. Those variations could lead to conflicting outcomes and conclusions and may also increase complexity for the LCA practitioner leading to high competence and resource requirements.

Within the research project*: Impacts on fuel producers and customers of conflicting rules for LCA,* the requirements of different LCA frameworks and their implications to fuel producers are investigated. Focus has been given on three specific frameworks that are identified as relevant or potentially relevant for fuel producers, namely: the recast of the EU Renewable Energy Directive (referred to here as RED II), the EU framework for Product Environmental Footprint (PEF), and the framework of Environmental Product Declaration (EPD). The aim of the project is to increase understanding on the different LCA frameworks available and identify whether the multitude of such frameworks gives conflicting recommendations for environmental improvements and fuel choices.

The three LCA frameworks listed above were applied in case studies. To illustrate the potential differences that the different frameworks may lead to, a variation of production pathways and feedstocks were selected including first generation as well as advanced biofuels.

Based on the results obtained it can be concluded that applying all three frameworks is not a straightforward task. The methods contain fundamental differences and are at different levels of development, maturity, and adoption. In certain situations, they can lead to diverging conclusions as a resuly of different quantitative outcomes for a specific production pathway, thus influencing decision making processes in different directions. Understanding those differences and underlying assumptions is important for understanding the variations in outcome.

The result for a specific fuel could differ substantially depending on the framework applied and the assumptions and interpretations made when applying this framework. Certain methodological parameters were identified to have a greater impact on the results than others:

- The three frameworks diverge in the methods applied for modelling waste management, which can be very important for the results when the biofuel is produced from waste.
- The frameworks diverge in what approaches are allowed for modelling processes with multiple products. This can be very important for the results when the fuel is co-produced with other products.
- The frameworks also diverge in how the electricity supply is modelled. This is not very important for the results in most of our case studies, because the production of these biofuels does not require a lot of electricity.

The study confirms that applying a framework like EPD or PEF in addition to RED II would require significant supplementary efforts. Not only because of different rules which were often contradicting or difficult to interpret but also because of additional data and reporting requirements. The need for expertise and resources is increasing for fuel producers to be able to provide EPD and PEF compliant assessments.

To enhance the development and harmonization of LCA approaches this project stresses the need for product specific rules (in the form of Product Environmental Category Rules (PEFCR) and Product Category Rules (PCR)) for renewable fuels. Future versions of all three studied frameworks should be clearer on how specific methodological choices are to be applied (e.g., when it comes to allocation and multifunctional processes) as well as when it comes to model electricity supply. RED for example shall be clearer on how to define the electricity region while EPD guidelines on how to define the electricity market.

Although it is not realistic to aim for a single unified LCA framework, the biofuel PCR and PEFCR can be developed with RED in mind. Some aspects of the PEF methodology can perhaps also be integrated into RED III that is currently under development. This would enhance the broader adoption of the frameworks among fuel producers. Finally, the involvement and engagement of the industry, and fuel producers themselves is very important. Industry initiatives are essential for the development of biofuel PCR and PEFCR while the general development of the three frameworks can also be influenced.

In this study, we also investigated the relationship between the LCA frameworks and schemes for chain of custody certification (CoCC), in particular schemes for mass balance certifications (MBC) to investigate to what extent these schemes complement or overlap with LCA. The purpose of MBC schemes and LCA are different, in the sense that the first aim at verifying the sources and sustainability of total amounts of raw materials used by tracking them throughout the value chain, while the second at quantifying specific environmental impact. The system boundaries are similar, since both cover the entire value chain, but may be applied differently depending on the detailed frameworks applied and choices made in applying the MBC schemes.

By identifying and clearly illustrating the variations among the studied frameworks the study enhances application, development, and harmonization of LCA, in a broader perspective, informs LCA practitioners but also decision makers and provides insights on how the identified challenges can be addressed.

SAMMANFATTNING

Användningen av livscykelanalys (LCA) som ett verktyg för att uppskatta miljöprestanda för en produkt eller tjänst på ett holistiskt och systematiskt sätt ökar. Bränsleproducenter kan behöva använda olika ramverk i olika sammanhang; internt för produktutvecklingsaktiviteter såväl som externt för kommunikation med kunder eller myndigheter. LCA-ramverken kan variera i omfattning, systemgränser (vilka livscykelstadier som ska beaktas) eller modelleringskrav (som t.ex. datakrav men också mer detaljerade metodiska egenskaper). De kan också variera när det gäller information de kan tillhandahålla i förhållande till produktens miljöprestanda. Dessa variationer kan leda till motstridiga resultat och slutsatser och kan också öka komplexiteten för LCA-utövaren, vilket leder till höga kompetens- och resurskrav.

Inom forskningsprojektet *Konsekvenser av motstridiga LCA-regelverk för producenter och användare av drivmedel* utreds kraven från olika LCA-ramverk och deras konsekvenser för bränsleproducenterna. Fokus har lagts på tre specifika ramverk som identifieras som relevanta eller potentiellt relevanta för bränsleproducenter: EU:s direktiv om förnybar energi (RED II), EU:s ramverk för produktmiljöavtryck (PEF) och ramverket för miljöproduktdeklaration (EPD). Syftet med projektet är att öka förståelsen för de olika LCA-ramverken som finns tillgängliga och att identifiera om mångfalden av sådana ramverk ger motstridiga rekommendationer för miljöförbättringar och bränsleval.

De tre LCA-ramverken som anges ovan tillämpades i fallstudier. För att illustrera de potentiella skillnaderna som de olika ramverken kan leda till valdes en variation av produktionsvägar och råvaror, inklusive första generationens samt avancerade biobränslen.

Resultatet visar att det inte är en enkel uppgift att tillämpa alla tre ramverken. Metoderna innehåller grundläggande skillnader och befinner sig på olika nivåer av utveckling, mognad och implementering. I vissa situationer kan de leda till motstridiga resultat (t.ex. olika kvantitativa resultat) för en specifik produktionsväg vilket därmed kan påverka beslutsprocesser i olika riktningar. Att förstå skillnaderna och underliggande antaganden är viktigt för att förstå variationerna i utfall.

Resultaten för ett specifikt bränsle kan skilja sig väsentligt beroende på det ramverk som tillämpas och de antaganden och tolkningar som görs vid tillämpningen av detta ramverk. Vissa metodologiska parametrar identifierades ha en större inverkan på resultaten än andra:

- De tre ramverken skiljer sig åt i de metoder som tillämpas för att modellera avfallshantering, vilket kan ha stor betydelse för resultaten när biobränslet produceras av avfall.
- Ramverken skiljer sig åt i vilka tillvägagångssätt som är tillåtna för modellering av processer med flera produkter. Detta kan ha stor betydelse för resultatet när bränslet samproduceras med andra produkter.
- Ramverken skiljer sig åt i hur elförsörjningen modelleras. Detta är inte särskilt viktigt för resultaten i de flesta av våra fallstudier, eftersom produktionen av dessa biobränslen inte kräver mycket el.

Studien bekräftar att tillämpning av ett ramverk som EPD eller PEF utöver RED II skulle kräva betydande kompletterande insatser, inte bara p.g.a. olika regler som ofta var motstridiga eller svåra att tolka, utan också p.g.a. ytterligare data- och rapporteringskrav.

Behovet av expertis och resurser ökar för att bränsleproducenter ska kunna tillhandahålla EPD- och PEF-kompatibla bedömningar.

För att förbättra utvecklingen och harmoniseringen av LCA-metoder betonar detta projekt behovet av produktspecifika regler (i form av Product Environmental Category Rules (PEFCR) och Product Category Rules (PCR)) för förnybara bränslen.

Framtida versioner av alla tre studerade ramverk bör vara tydligare med hur specifika metodval ska tillämpas (t.ex. när det gäller allokering och multifunktionella processer) samt när det kommer till modellering av elförsörjning. RED ska till exempel vara tydligare med hur man definierar elregionen medan EPD behöver riktlinjer för hur man definierar elmarknaden.

Även om det inte är realistiskt att sikta på ett enda enhetligt LCA-ramverk, kan biobränsle-PCR och PEFCR utvecklas med RED i åtanke. Vissa aspekter av PEF-metoden kan kanske också integreras i RED III. Detta skulle öka det bredare antagandet av ramarna bland bränsleproducenterna. Slutligen är engagemanget från industrin och bränsleproducenterna själva mycket viktigt. Branschinitiativ är väsentliga för utvecklingen av biobränsle-PCR och PEFCR, samtidigt som den allmänna utvecklingen av de tre ramverken också kan påverkas.

I denna studie undersökte vi också sambandet mellan LCA-ramverken och systemen för spårbarhetscertifiering (CoCC), i synnerhet system för massbalanscertifiering (MBC) för att undersöka i vilken utsträckning dessa system kompletterar eller överlappar med LCA. Syftet med MBC-system och LCA är olika i den mening att det första syftar till att verifiera källorna och hållbarheten för totala mängder råvaror som används genom att spåra dem genom hela värdekedjan, medan det andra syftar till att kvantifiera specifik miljöpåverkan. Systemgränserna är likartade eftersom båda täcker hela värdekedjan, men de kan tillämpas på olika sätt beroende på de detaljerade ramar som tillämpas och de val som görs vid tillämpningen av MBC-systemen.

Genom att identifiera och tydligt illustrera skillnader mellan de studerade ramverken förbättrar studien användning, utveckling och harmonisering av LCA. I ett bredare perspektiv kan den också informera LCA-utövare samt beslutsfattare och ge insikter om hur de identifierade utmaningarna kan hanteras.

CONTENTS

1 INTRODUCTION

Life cycle assessment (LCA) is a commonly applied framework for estimating the environmental performance of products and services by taking into considerations all activities related to their life cycle: from raw material extraction, to production and disposal. LCA and other life cycle calculations are increasingly used to guide decisions and the development towards improved environmental performance of products or services.

The LCA methodology has developed and matured throughout the years. The need for consistent assessment processes that enhance transparency and comparability has led to the development of customized approaches, detailed guidelines, and product specific tools. The focus of this work has been on LCA frameworks and tools that are relevant or potentially relevant for fuel producers.

The Renewable Energy Directive (RED) of the European Commission (2018a) stipulates rules for how to calculate the reduction in greenhouse gases (GHG) obtained in a life cycle perspective through the use of renewable fuels. A different set of equally detailed rules apply when companies develop life-cycle based Environmental Product Declarations (EPDs) produced for marketing purposes. The detailed rules are specified by Product Category Rules (PCR) that differ slightly between product groups. PCRs have been developed for an expanding number of product groups (EPD International, 2019). For building products for example, they have even been published as an international standard (ISO 21930:2017). A third framework introduced and currently under development by the European Commission (2018b) Product Environmental Footprints (PEF) is a type of LCA that can be used for product declarations and possibly also for policymaking. Detailed rules (PEF Category Rules; PEFCRs) are being developed also within this framework, but since the framework is more recent it covers fewer product groups.

The requests for LCAs that fuel producers can get in the future may require the application of different methodological frameworks as the ones listed above or even additional ones depending on geographical boundaries and their end market or customers. RED is a very commonly applied framework among fuel producers in Europe as a result of compliance reporting. In the short term however, fuel producers are likely to be asked to provide input data to EPDs mainly because a fuel is used in the life cycle of most other products. No PCR for biofuel exists yet, although the need has been previously identified (Hallberg et al., 2013). When a PCR for biofuel has been developed, fuel producers can opt to develop their own EPDs.

The listed frameworks (RED; EPD; PEF) vary in scope, system boundaries i.e. what life cycle stages to be considered, or modelling requirements such as data demands but also more detailed methodological features. They may also vary in terms of information they can provide in relation to the environmental performance of the product. Those variations could lead to conflicting outcomes and conclusions and may also increase complexity for the LCA practitioner leading to high competence and resource requirements.

Within the ICON project (Impacts on fuel producers and customers of conflicting rules for LCA) presented in this report the requirements of different LCA frameworks and their implications to fuel producers are investigated. Focus has been given to the three frameworks listed above namely: RED, EPD and PEF.

1.1 AIM OF THE PROJECT

The aim of the project and the work presented in this report is to increase understanding on the different LCA frameworks available, especially the ones relevant or potentially relevant for fuel producers and identify whether the multitude of such frameworks gives conflicting recommendations for environmental improvements and fuel choices. Moreover, it aims to illustrate the practical consequences on LCA practitioners but also fuel producers relating for example to resources, cost, complexity and more.

By identifying and clearly illustrating the variations among the studied frameworks the study is expected to enhance application, development, and harmonization of LCA, in a broader perspective, inform LCA practitioners but also decision makers and provide insights on how the identified challenges can be addressed.

1.2 METHODOLOGY

In this work three frameworks are considered and applied in case studies on selected transport fuels namely:

1. the recast of the EU Renewable Energy Directive (referred to as RED II)
2. the framework of Environmental Product Declaration (EPD)
3. the EU framework for Product Environmental Footprint (PEF)

The cased studies were identified and selected from the project group and in cooperation with representatives from industry. To illustrate the potential differences that the different frameworks may lead to, a variety of production pathways and feedstocks were selected.

Eight fuel production pathways were assessed and are presented in this report as listed in Table 1.

Table 1. Fuel production pathways assessed in the project.

Fuel	Feedstock	Classification
Hydrotreated vegetable oil (HVO)	Used cooking oil (UCO)	Recycled feedstock
Biogas	Municipal food waste	Recycled feedstock
Rapeseed methyl ester (RME)	Rapeseed oil (RSO)	Primary feedstock
HVO (based on RSO)	Rapeseed oil (RSO)	Primary feedstock
Ethanol	Corn	Primary feedstock
Advanced ethanol	Food – Bakery residues	Recycled feedstock
Advanced ethanol	Sawmill residues	Process residues
Pyrolysis oil	Used vehicle tyres	Recycled feedstock

The collection of case studies is used as basis for identifying the most important methodological differences between the three frameworks. The meta-analysis performed explains why different frameworks lead to different results. In this part of the study, we also discuss to what extent each framework leads to reproducible assessments. An assessment is less reproducible if the framework explicitly allows for the use of different methods, or if the calculation rules in the framework are unclear.

To widen the perspective further, the project also includes reflections on the connection between the LCA methods used within the case studies and the provisions of certification schemes for certification of so-called mass balance systems.

1.3 DELIMITATIONS

For performing an LCA study, detailed data on the flows of energy, materials, or other resources as well as on flows leaving the studied system are needed. Here certain simplifications were allowed in order to be able to perform the analysis. Four of the case studies are based on existing processes while others are based on literature data. The focus has been on understanding the overall product system and how this is affected by each framework and less on extensive data collection. The numerical values, when available shall be treated with care as different cases may depend on different level of detail. This is not expected to influence the outcome of this work as comparing or ranking the fuels was out of the scope of this project.

It should be also noted that the focus of the case studies has been on the climate change indicator because that was the only indicator available in all three frameworks.

1.4 STRUCTURE OF THE REPORT

After providing the background, key objectives and methodology applied, the remaining sections of the report are structured as follows: in Chapter 2 a brief overview and background information to the three LCA frameworks applied in this work is provided. Chapters 3-10 present the eight case studies performed, containing details on process data, methodological variations and assumptions related to the three frameworks and final results. Based on these, Chapter 11 contains the meta-analysis performed where the results and implications from the case studies are discussed. Chapter 12 provides reflections on the connection between LCA frameworks and mass balance certification systems. In Chapter 13 the key conclusions and learning outcomes from the project are summarized.

2 OVERVIEW OF THE STUDIED FRAMEWORKS

In this section a short background and overview of the studied frameworks is provided. The overview focuses on the scope and selected methodological choices to be considered for each of the three frameworks included in this report such as the system boundary, approach for multifunctional processes (i.e., processes that produce more products than the product under assessment), approach for handling processes involving reuse, recycling, and energy recovery as well as the assessment of different environmental impacts.

Table 2 provides a summary of the analysis performed in relation to the three studied frameworks while more details are given in sections 2.1-2.3. The analysis in this chapter is at rather generic level. Additional guidelines and exemptions identified for specific types of biofuels are discussed in the following chapters and when the frameworks are applied to the case studies.

For the analysis, official documents of the frameworks are used. Any updated documents published during or after the completion of the project were not considered. It shall be also noted that EPD guidelines refer to the specific guidelines published by the International EPD® System, that is one EPD operator.

Table 2 Overview of the three frameworks analysed and applied in this work: RED II, EPD and PEF. Information is collected from the official documents of the frameworks (European Commission (2018a); EPD International (2019); European Commission (2018b)).

	Renewable Energy Directive (RED II)	Environmental Product Declaration (EPD)	Product Environmental Footprint (PEF)
General description	The RED is a regulatory scheme targeted on renewable energy in which sustainability and greenhouse gas (GHG) emissions criteria are determined and with which EU member states have to comply	EPD is a Type III environmental declaration scheme which provides a standardized and voluntary-based method of quantifying the environmental impact of a product.	PEF is developed by the European Commission with an ambition of providing a new and standardized method of assessing an environmental impact of a product, service, or organization
Purpose	GHG emissions reporting scheme to assess compliance with the emission reduction targets	To communicate environmental information in a way that enables comparison between products with the same function	To measure and communicate the environmental impact of products, services, or companies in a coherent and harmonized way
Intended Audience	National and EU authorities	Mainly business to business and sometime business-to-consumer	Business to business and business to consumer
Functional Unit	1 MJ of fuel	Shall be specified by the Product Category Rules (PCR)	Shall be specified by the Product Environmental Footprint Category Rules (PEFCR)
System Boundaries	Cradle-to-grave Can be case specific based on the studied system	Cradle-to-grave Can be case specific based on the studied system	Cradle-to-grave Can be case specific based on the studied system
Type of LCA (attributional or consequential)	Attributional LCA	Attributional LCA	A combination of attributional and consequential elements
Allocation: Multifunctional process	Allocation based on energy content. For cogeneration of electricity and heat, different allocation rule is applied specified by a given formula	Decision hierarchy i) subdivision, ii) allocation based on physical relationship, iii) allocation based on other relationship. Further specifications shall be specified in the PCR	Decision hierarchy i) subdivision or system expansion, ii) allocation based on physical relationship, iii) allocation based on other relationship
Allocation: Recycling, Reuse and Recovery	Feedstocks classified as waste and residues shall be considered to have zero GHG emission up to the collection of the waste	Defined by the Polluter Pays Approach	Defined by the Circular Footprint Formula (CFF)
Environmental Impact Assessment	Climate Change (expressed in g CO_2 eq.)	7 default environmental impact categories Additional can be specified in the PCR	16 default environmental impact categories
Selected characterization factors applied for GWP 100– Climate Change	Fossil CO_2=1; Biogenic CO_2=0; Any CH_4=25; N_2O=298	Fossil CO_2=1; Biogenic CO_2=0; Any CH_4 = 28; N_2O = 265	Fossil CO_2= 1; Biogenic CO_2= 0; Fossil CH_4 = 36.8; Biogenic CH_4= 34; N_2O = 298

2.1 THE RENEWABLE ENERGY DIRECTIVE (RED)

The Renewable Energy Directive (Directive EU 2018/2001), commonly referred to as RED, is introduced and established as a regulatory framework to support the increased use of renewable energy in the European Union (EU) while also reducing emissions of greenhouse gases (GHGs). RED sets national targets on the share of renewable energy (in the form of biofuels, bioliquids, biomass fuels etc.[1].) in each member state. Moreover, it sets sustainability criteria, including GHG emission reduction criteria that need to be fulfilled. The criteria are laid out directly in the directive, its annexes and supporting delegated acts. Further, in some respects the detailed regulation may be further specified on member state level. Biofuels, bioliquids and biomass fuels need to fulfil these sustainability criteria to contribute to the national and EU targets for renewable energy specified in the directive and to be eligible for financial support. The sustainability and the GHG emissions saving criteria in apply regardless of the geographical origin of the biomass.

RED was firstly introduced in 2009 and has been in force up until now. In 2018 a recast of RED was published (known as RED II) where certain modifications and updates were considered. RED II is in force in Sweden since July 2021 (Swedish Energy Agency, 2021).

RED II applies for electricity, heat, and transportation fuels. The necessary savings in GHG emissions for transport biofuels depends on when the plant in which they are produced was inaugurated. Newer plants have higher requirements. For plants starting operation from 1st January 2021 a minimum of 65% reduction is required raising to 70% until the end of 2025 and 80 % thereafter.

System boundary

To account for the GHG emissions savings a specific methodology is described in the directive. In this work we refer and apply the updated guidelines provided in RED II. The methodology applies a life cycle perspective and is described in Annex V of the directive. The life cycle GHG emissions are calculated according to the following equation:

$$\mathbf{E = e(ec) + e(l) + e(p) + e(td) + e(u) - e(sca) - e(ccs) - e(ccr)}$$

where,

E = total emissions from the fuel used
e(ec) = emissions from extraction and cultivation of raw materials
e(l) = emissions from the change in carbon stock due to land-use change
e(p) = emissions from processing of fuels including the production of chemicals or products used in the process and fossil input (whether or not actually combusted in the process)
e(td) = emissions from transport and distribution
e(u) = emissions from fuel in use
e(sca) = emission saving from improved agriculture management
e(ccs) = emission saving from CO_2 capture and geological storage

[1] Biomass fuels refer to gaseous and solid fuels produced from biomass; biofuels refer to liquid fuel for transport produced from biomass; bioliquids refer to liquid fuel for energy purposes other than for transport, including electricity and heating and cooling, produced from biomass.

e(ccr) = emission saving from CO_2 capture and replacement

Hence, the system boundary for the RED II framework can be considered cradle-to-grave.

Functional unit

The functional unit in the RED II framework is specified as 1 MJ of fuel.

Type of LCA

RED II is not an LCA framework as such so the type of LCA is not explicitly described in the calculation method. It has elements from both attributional LCA (ALCA) and consequential LCA (CLCA). ALCA looks at the share of the global environmental impact of the product while the CLCA looks at the change in the environmental impact when the demand for the functional unit is changed (Brandão *et al*., 2021). The RED II framework has the element of CLCA when it aims to calculate the saving of the GHG emissions compare to the fossil fuel i.e., look at the change of the emissions as a consequence of using different type of bioenergy. The use of substitution, which reflects the consequential approach, is also mentioned even though it is not recommended to use. On the other hand, the framework allows the use of average data, which means that it is conformed with the ALCA. Hence, the framework can be considered as mainly ALCA.

Allocation: multifunctional processes

The directive states that all co-products are to be allocated based on their energy content, which is determined by the lower heating value (LHV). For cogeneration of electricity and heat, different allocation rules are applied (for details see (European Commission, 2018a). Waste and residues are not considered as co-products and shall have no emissions allocated to them. The same also applies for feedstocks as listed in Annex IX part A and B for the production of biogas for transportation and advanced biofuels. For co-products with negative energy content, their energy value shall be set to zero. Substitution is possible when it is used for the purpose of policy analysis. The approach described above is to be used for the regulation of individual economic operators.

Allocation: recycling and recovery

Waste and residues such as treetops and branches, straw, husks, cobs and nut shells, and residues from processing and bagasse are considered to "…have zero life-cycle greenhouse gas emissions up to the process of collection of those materials…" European Commission (2018a). This indicates that waste and residues shall have no emissions from the previous life cycle and up to their collection.

Accounting of biogenic carbon

RED II does not account the capture of CO_2 from plants. Consequently, emissions from fuel in use, e(u), is to be taken as zero for biofuels and bioliquids. For bioliquids and biomass fuels (such as biogas), the emissions of N_2O and CH_4 are to be included.

Environmental impact assessment

Since the RED framework only focuses on emissions of GHGs, it only measures the impact on climate change, which is expressed as grams of CO_2 equivalent (g CO_2 eq.). The climate change impact takes into account the emissions of CO_2, CH_4 and N_2O and their emission factors are specified in the framework as listed in Table 2 based on the values from the IPCC 4th Assessment Report. The GHG emissions savings from biofuels and bioliquids is calculated in relation to a fossil fuel comparator. The fossil comparator for biofuels and biomass fuels used as transport fuels is 94 g CO_2 eq./MJ.

Data quality

Actual data or a combination of actual and default values shall be used in the calculation. However, average data is also allowed; for example average values for the emissions from cultivation and average emission intensity of the production and distribution of electricity in a defined region. When actual process emissions are not available, the directive has also provided typical values and default values for certain parameters such as e(ec), e(p) and e(td). Typical values are representative values of the GHG emissions intensity and GHG emissions savings of different type of biofuel, bioliquid or biomass fuels, as estimated from an EU perspective. The typical values are set conservatively to provide incentives for actual values calculations. Default values are derived from the typical values by applying pre-determined factors. Default values to be used instead of the actual value, may be specified in the directive.

2.2 ENVIRONMENTAL PRODUCT DECLARATION (EPD)

Environmental Product Declaration or EPD is a Type III environmental declaration which is compliant with the ISO 14025 standard. It provides an independently verified environmental information for products or services based on LCA. An EPD can be done voluntarily by a company and the information is used primarily for business-to-business communication. There are several programme operators that offer publication of EPDs and the framework's methodology can vary for different operators. In this study, the framework followed by EPD International was used as described in the General Programme Instruction (GPI) documentation (EPD International, 2019). In addition to that an EPD normally follows a so-called Product Category Rule (PCR) which contains specific guidelines and rules for a specific product type. As a PCR for biofuels has not yet been developed the general method description provided by the GPI is applied to the case studies unless otherwise stated. At the time that this project started, GPI version 3.01 is the one that is available, and it is also the one that is used. However, a newer version of GPI has been released later but this version is not considered in this project.

The GPI v.3.01 provides a general description of LCA methodology which follow the ISO 14040/14044 standard but with some pre-conditions that are already set.

System boundary

The default system boundary of the EPD framework is cradle-to-grave. All relevant processes should be included to prevent the loss of information at the final product. The International EPD® System divides the life cycle of a product into three stages:

- Upstream processes – from cradle-to-gate
- Core processes – from gate-to-gate
- Downstream processes – from gate-to grave

The division of the life cycle stages is because each stage has different data quality rules but also to facilitate the presentation of results.

Functional unit

The choice of functional unit of the EPD framework is specified in the PCR. In case that a full life cycle is not covered and the function of the product in terms of use is not known, a so-called declared unit can be used instead of the functional unit. A declared unit is related to the typical use of product e.g., 1 kg, 1 m, or 1 m^2 of a product.

Type of LCA

The methodology followed in the EPD framework is described as an attributional LCA.

Allocation: multifunctional processes

Allocation among co-products shall be done according to the allocation rules provided in the GPI v.3.01. The rules are as following:

- Allocation shall be avoided through sub-dividing the processes, so that the input and output data related to the sub-processes can be obtained. System expansion according to the ISO14044 is not allowed due to the nature of the framework being strictly attributional.
- When allocation cannot be avoided, partitioning of the input and output to different products or services shall be done based on their underlying physical relationship.
- If allocation based on physical relationship cannot be applied, partitioning based on other relationships is also possible. A sensitivity analysis needs to be conducted when economic value is used as basis for allocation.

Allocation: recycling and recovery

When the process involves reuse, recycling or recovery, EPD applies the Polluter Pays Principle (PPP) to separate the impact of the secondary material from its previous life cycle. The PPP means that the polluter or the waste generator should bear the cost or the burden of the product. The point at which the waste generator stops carrying the burden is at the point where waste has the lowest market value. Hence, the waste generator has to carry the full environmental impact of the previous life cycle till the waste is transported to a scrapyard or to the gate of waste processing plant/collection site. The impact from the process that occurs after this point i.e., the point where waste is processed for reuse, recycled, or recovered (as energy) is then allocated to the second product/life cycle.

Environmental impact assessment

EPD considers seven default environmental impact categories: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Oxidant Formation Potential (POFP), abiotic depletion potential – elements, abiotic depletion potential – fossil fuels and Water Scarcity Footprint (WSF).

GWP over 100 years (GWP100) is used to indicate the climate change impact category. The GWP100 shall be calculated according to CML 2001 baseline, version January 2016, which was originally from IPCC 2013. EPD requires four types of GWP to be reported. These four types of GWP are based on the origins of the GHG emissions and removals: GWP-fossil, GWP-biogenic, GWP-land use and land use change (LULUC) and GWP-total. The GWP-total is the sum of the three aforementioned types of GWPs. The characterization factors of the GHGs are noted in Table 2.

Accounting of biogenic carbon

The emissions and removals of GHG from human food and animal feed that become the ingested part of the product shall not be included. GHG emissions (except CO_2) originating from degradation food/feed waste and enteric fermentation are to be included.

When a secondary material is used, the stored carbon that enters the system boundary shall be accounted for as if it were a primary material.

Data quality

In general, specific data are to be used whenever possible. For the core process, it is mandatory to use specific data. Generic data can be used for upstream and downstream when specific data are not available. The generic data should be representative for the process included in the EPD.

The modelling of electricity should be done in the following priority:

- Specific electricity mix as generated or purchased
- National residual electricity mix
- National electricity production mix or electricity mix on the market

2.3 PRODUCT ENVIRONMENTAL FOOTPRINT (PEF)

Product Environmental Footprint or PEF is a method developed by the European Commission aiming to provide a common and harmonized way of measuring and communicating environmental impact of products or services at a European level (European Commission, 2012). A life cycle perspective is applied when assessing and quantifying the environmental impacts. Similar to EPD, PEF needs a Product Environmental Footprint Category Rule (PEFCR) which provides the rules for performing a PEF for different product categories. However, the PEF framework has not been fully developed yet. Between 2013-2018, the PEF framework was under a pilot phase where more than 280 companies were voluntarily testing the frameworks and developing specific rules for different products groups or services (European Commission, 2022). PEF is currently under a transition phase before the adoption of policies regarding the implementation of PEF.

The PEF framework is described in general in the PEF Guide (European Commission, 2012) and since the PEFCR for biofuels is not available, some more specific rules and guidance were obtained in the PEFCR Guidance version 6.3 (European Commission, 2018b).

System boundary

The PEF framework defines the system boundary from cradle-to-grave, that is all stages from raw material extraction, processing, production, distribution, use stage and the end-of-life treatment of the product.

Functional unit

In PEF, the functional unit is called unit of analysis. The unit of analysis defines the function(s) and duration of the product both qualitatively and quantitively. For example, it shall answer the questions of “what function”, “how much”, “how well” and “how long”.

Type of LCA

The methodology used in the PEF framework is described as a combination of attributional and consequential LCA. The framework allows the use average data which reflects the nature of ALCA and at the same time encourages the use of system expansion and substitution approach, which are characteristics of the CLCA.

Allocation: multifunctional processes

The PEF has a so-called decision hierarchy that provides guidance on how to model processes that produce more than one product or service (multifunctional processes). The hierarchy is:

- Avoid allocation through subdivision or system expansion. Subdivision is when the multifunctional processes are divided so that input flows associated with each process output can be separated. System expansion here refers to the expansion into a system with multiple functional outputs by including each function related to the co-products.

- If allocation problem cannot be avoided through subdivision or system expansion, then allocation based on relevant underlying physical relationship should be applied. This physical allocation can also be modelled through direct substitution if a product is directly substituted. A direct substitution is explained in the PEF Guide (European Commission, 2012) as when “a direct, empirically substitution effect can be identified”. For example, when manure nitrogen applied on land can be directly substituted with an equivalent amount of specific fertilizer nitrogen.

- Allocation based on other relationship can be applied, for example based on economic value. Here the PEF methodology includes indirect substitution as an option.

Allocation: Recycling and/or energy recovery

For processes that involve recycling and/or energy recovery, allocation of environmental impact of the previous and the subsequent life cycle is needed. The PEF framework defines the so-called Circular Footprint Formula (CFF) to account for the burdens and benefits of these processes. The CFF can be divided into three parts: material+ energy +disposal

Material: $(1-R_1)E_v + R_1 \times \left(AE_{recycled} + (1-A)E_v \times \frac{Q_{sin}}{Q_p}\right) + (1-A)R_2 \times (E_{recyclingEoL} - E_v^* \times \frac{Q_{sout}}{Q_p})$

Energy: $(1-B)R_3 \times (E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec})$

Disposal: $(1-R_2-R_3) \times E_D$

The parameters used in the CFF include the allocation factors (A and B factor), quality of primary and secondary material (Q_p, Qs_{in} and Qs_{out}), proportion of material in different system (R_1, R_2 and R_3), specific emissions and resource used (E_v, E_v*, $E_{recycled}$, $E_{recyclingEoL}$, E_{ER}, E_D), efficiency of the energy recovery process for heat and electricity ($X_{ER,heat}$ and $X_{ER,elec}$) and lastly the lower heating value (LHV). More specifically:

A = allocation factor of burdens and credits between supplier and user of recycled materials. The A factor is predefined for different type of products and can have a value 0.2, 0.5 or 0.8. For the product with unspecified A factor, A = 0.5 shall be used.

R_1 = proportion of the input material that has been recycled from the previous system.

R_2 = proportion of the material in the product that will be recycled or reused in the subsequent system.

E_v = specific emissions and resources used that arise from the acquisition and pre-processing of virgin material.

$E_{recycled}$ = specific emissions and resources used that arise from the recycling process of the recycled or reused material, including collection, sorting, and transportation process.

Details on the definitions of each parameters can be found in the Appendix of this report and in the PEFCR Guidance v.6.3 pp. 113-130.

The quality ratio such as Qs_{in}/Q_p is defined at the point of substitution. The point of substitution is the point in the value chain where secondary materials substitute primary materials. The choice of this point of substitution is crucial as it also affect the interpretation of E_v and E_{rec}.

Environmental impact assessment

There are 16 environmental impact categories that are considered in the PEF framework. Climate change indicated by GWP100 (kg CO_2eq) is one of them (others include Acidification, Eutrophication, Human Toxicity and more[2]). The impact on climate change is in turn divided into different sub-categories:

- Climate change – fossil: account for GHG emissions to any media from oxidation or reduction of fossil fuels e.g. combustion, digestion, landfilling)
- Climate change – biogenic: account for the carbon emissions to air (CO_2, CO and CH_4) from aboveground biomass through oxidation or reduction and the CO_2 uptakes from the atmosphere by means of photosynthesis.
- Climate change – land use and land transformation: account for carbon uptakes and emissions (CO_2, CO and CH_4) arising from changes in carbon stock that is caused by land use and land use change. This includes biogenic carbon exchanges from deforestation, road construction, soil carbon emissions and other soil activities.

[2] The complete list of environmental impact indicators and associated characterization factors can be found in the PEFCR Guidance version 6.3 (European Commission, 2018b).

A simplified model of the Climate change – biogenic should be done where only biogenic methane emissions influence the climate change impact e.g., food related LCAs. The simplified model suggests that only the emissions of biogenic methane is modelled, no further biogenic emissions and uptakes from atmosphere are modelled and that the release of the biogenic methane shall be modelled first.

The characterization factors for the GHGs are adapted from the IPCC 2013 where the factor for fossil methane is corrected by taking into consideration that in a longer time horizon, all of the fossil methane is converted into CO_2. In the IPCC, this is only true for biogenic methane. The characteristic factors of the GHGs are presented in Table 2. Biogenic carbon that are emitted after 100 years is considered as stored carbon and has a negative contribution. When all the emissions and uptakes are modelled separately, the characterization factors for biogenic uptake and emissions have to be set to zero.

Data quality

In general, company-specific data should be used whenever possible or at least for the foreground data (data that are under direct influence of the decision maker). Generic data can be used and should be used only for background data (data that are influenced indirectly by the foreground system).

When company-specific data is used, the electricity shall be modelled according to the following hierarchy:

- Supplier specific electricity product
- Supplier-specific total electricity mix
- "Country-specific residual grid mix, consumption mix" - data available at https://lcdn.thinkstep.com/Node/.

2.4 MASS BALANCE MODELS AND CERTIFICATION SCHEMES

The increasing focus on converting production to sustainable renewable or recycled feedstocks, makes it increasingly important for companies to be able to follow and control their supply chain, but also to be able to transparently communicate and credibly verify it. Chain of custody models are used to monitor and control the flow of materials through the supply chain (see Figure 1). Those models show the origin of feedstocks used, the different conversion and transportation steps in the chain, and the losses incurred in these steps, so that a company can trace its use of, for instance, bio-based or recycled material back to the source.

There are several standards and chain of custody certification (CoCC) schemes that set up principles for book-keeping of inputs and outputs of certified materials and products. In addition, the

CoCC scheme is used to verify the sustainability of this supply chain.[3] To be able to transparently communicate and credibly verify its supply chain, the company is, in general, certified against the principles, by an independent certification body. The certification body certifies that the company follow the provisions laid out in the standard or certification scheme for the products and processes included in the certification.[4]

The mass balance concept refers here to the use of one type of chain of custody models. In simplified terms, there are four different chain of custody models used: Identity preservation models, segregated models, mass balance models, and book and claim models. The first two models cannot be used for situations where renewable or recycled materials are mixed with fossil material. In book and claim models, certificates of renewable/recycled material use can be traded, without a direct linkage to the actual material flows. In mass balance models, materials, or products with a set of specified characteristics (e.g., based on renewable or recycled raw material) may be mixed with materials or products without that set of characteristics. 5 The share of renewable material in the product may then be referred to as a percentage or a share. Depending on the system used, and the claims made, this share may be a known proportion or an average across different outputs or time periods. (ISO/DIS 22095:2019; ISEAL Alliance, 2016)

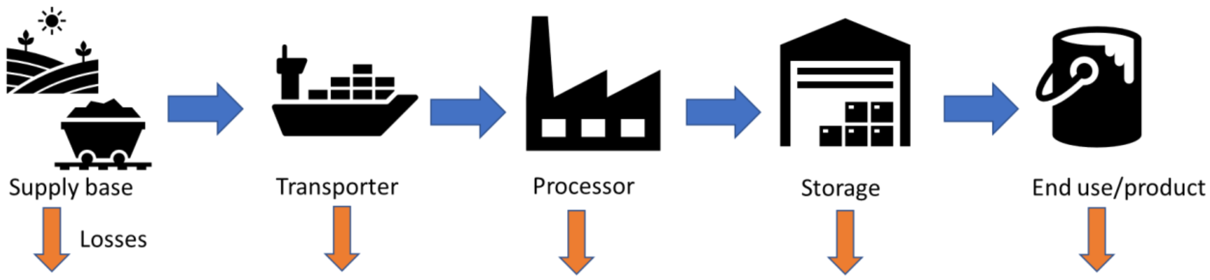

Figure 1. Generalized illustration of a chain of custody from raw material to final product. In the following simplified illustrations, omitting the transportation and storage stages, are used.

Mass balance certification (MBC) schemes are thus a sub-set of CoCC schemes used for value chains in which raw material with different sustainability properties (e.g., bio-based and fossil) are mixed in the production of one or several products (see Figure 2). Typical examples of such value

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[3] A certification scheme is strictly the organization, governance and stakeholders that issues and holds a set of provisions, against which a company, product or proves can be certified. A certification scheme is, in general, provided by an organization that develops and sells the set of provisions and related services. However, here we use the term "certification scheme" more loosely, to describe both the organization and the set of provisions it issues.

[4] The difference between standards and certification schemes are not self-evident. In addition, the term "standard" is used in different ways. For more detail, see Nyström *et al.* (2020).

[5] The term "mass balance" can also be used as directly signifying the application of conservation of mass to the analysis of a physical system. The use of the term Mass balance as a chain of custody model is of course derived from this physical meaning. However, the definitions differ and the concepts should not be confused.

chains include chemical industry and biofuel production plants, where both renewable and fossil raw material are mixed and processed together to produce several different end-use products.

The purpose is to make it possible to claim that a certain share of the products, or one of the products, are based on sustainably sourced material (e.g., biobased). The MBC scheme includes thus a set of provisions for how this allocation of materials can be done. Some areas that are commonly included in these provisions are:

- The system boundary of the mass balance – whether the mass balance need to be made for a specific process, a specific site or for a group of sites.
- Whether the calculation of the balance need to be based on site specific yields for the specific material (e.g., bio-yields) or if standardized values can be used.
- Whether the properties (e.g., being linked to bio-based raw material) can be freely attributed between products from the site.

The concepts used for certification based on mass balance principles are complex and different standards and certification schemes apply different provisions, for example in relation to physical and chemical traceability of material flows. In Nyström *et al*. (2020), different approaches to applying the mass balance concept were further explored.[6]

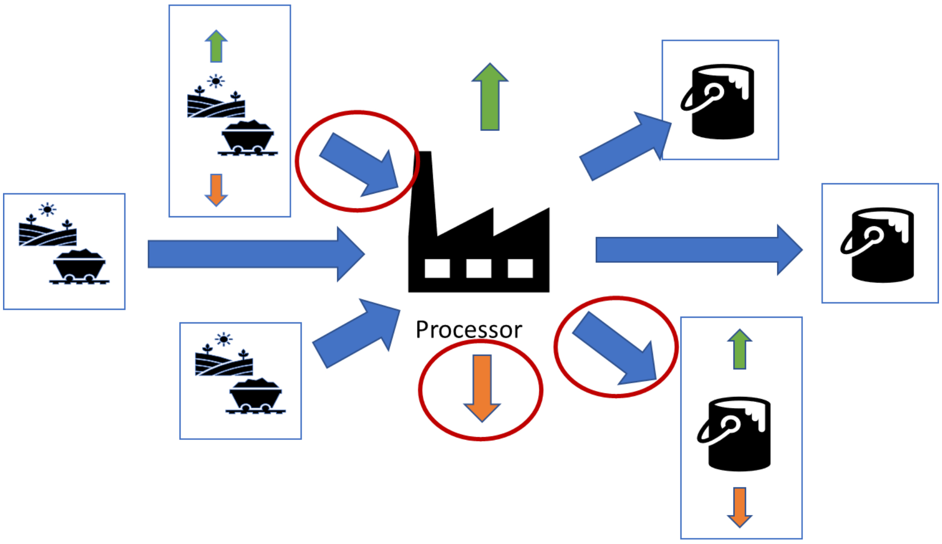

Figure 2. Illustration of the specific linkages in focus of an MBC scheme.

Another sub-set of CoCC schemes are certification schemes that are used to verify the compliance of the EU RED II. To simplify the control of the criteria, the commission has approved, in total, 15 certification schemes that can be used for verifying the compliance by certifying the sustainability

[6] The purpose of Nyström *et al*. (2020) was to increase the understanding of the use of the mass balance concept in the chemical industry, and to describe the approaches, provisions and delimitation of standards and certification schemes that this industry is using. The study provides a starting point and main source for the input related to MBC schemes in this report.

of the value chain from feedstock to fuel. The producer can then choose to prove compliance by being certified by one of these schemes.

Examples of RED approved certification schemes include ISCC EU, RedCert-EU and RSB EU RED. The same organizations that issue the provisions used for RED certification also issue MBC schemes. The MBC schemes can then be used to certify the chain of custody for products that are *not* covered by EU fuel sustainability regulations. The MBC schemes corresponding to the RED schemes mentioned above, are ISCC PLUS, REDCert[2] and RSB Advanced Products (RSB AP).[7]

Which aspects of sustainability that are included in different certifications vary between certification schemes and between what is included in the company specific certifications. In general, however, verification of actual *emissions* or quantification of environmental impact is not included. One exception is the verification of GHG emissions, which is mandatory for RED approved certification schemes (and for RSB AP) and can be added as a voluntary add-on in ISCC PLUS and REDCert[2].

[7] For more details on these organizations, see respective web page: www.iscc-system.org; www.redcert.org and www.rsb.org.

3 HVO FROM USED COOKING OIL (UCO)

Hydrotreated Vegetable Oil (HVO) is biobased diesel that can be produced from a wide range of raw materials such as vegetable oils, animal fats from slaughterhouse wastes or from Used Cooking Oil (UCO). In this case study, HVO from UCO is considered. The UCO is assumed to be collected within Sweden. The value chain starts from the purchase of UCO from UCO suppliers. The UCO is then treated and used as a feedstock to produce HVO.

The production of the HVO uses hydrogen to treat UCO in two stages. Firstly, the UCO which contains triglycerides is saturated and then treated further to produce fatty acids. The second stage is to remove oxygen from the fatty acids, with or without hydrogen, to produce the paraffinic hydrocarbons which is the HVO. The production processes produce propane, carbon dioxide and small amount of methane. The propane and methane can be used as fuel gas in the HVO production process, and the excess propane can also be sold on the market. The quality of the HVO such as cold flow properties can be improved further by isomerization and/or cracking process. However, in this case study, the isomerization and cracking processes were excluded as the major source of emissions comes from the main HVO processes.

The produced HVO is then shipped to the five major depots in Sweden and then distributed to smaller fuel stations. The value chain considered includes the following steps:

- Collection of UCO
- Pre-treatment of UCO
- Transport of UCO to the HVO production site
- HVO production
- Transportation and distribution
- Combustion of HVO in a heavy-duty truck (class EURO 5)

The data used in this case study to assess the environmental impact of the HVO is based on specific data (for HVO processing), generic and average data which were obtained from scientific literature databases and published company reports. The result from this case study was part of a master thesis conducted by Jogner & Nojpnaya (2021). However, due to updates in the interpretation of the PEF framework, the PEF result is revised.

3.1 SYSTEM BOUNDARIES

The system boundaries in relation to different frameworks applied to the case study on HVO are shown in Figure 3.

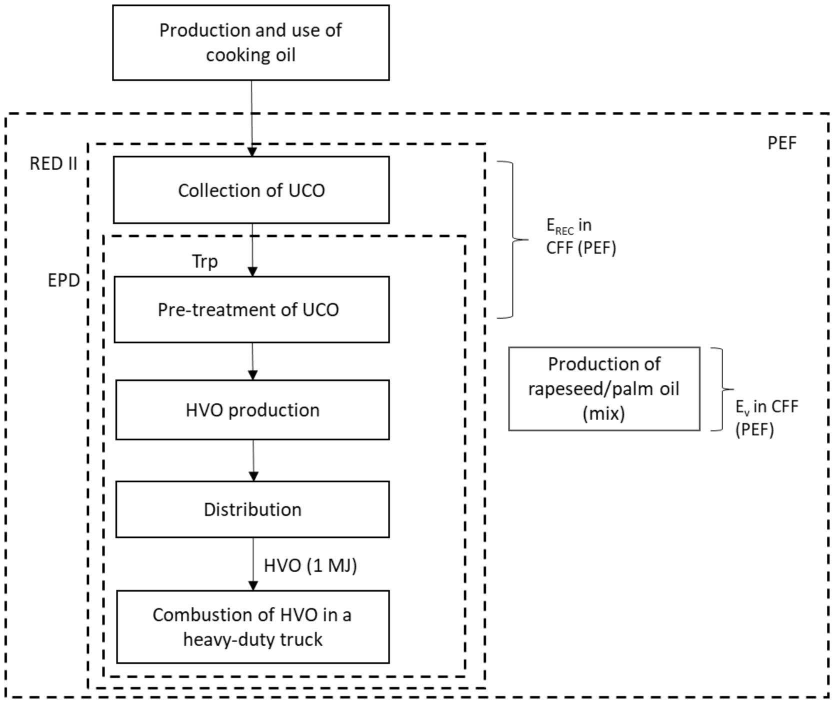

Figure 3. System boundaries in relation to the methods applied; RED II, EPD and PEF.

The three methods result in system boundaries that are quite similar to each other. The system boundaries for RED II and PEF are similar except that the PEF framework also takes into account the impact from substituted virgin material as a result of applying the CFF. The system boundary according to the EPD framework excludes the collection of UCO. The production of virgin cooking oil and the use of cooking oil are outside the system boundary.

3.2 KEY INPUT DATA AND ASSUMPTIONS

The functional unit used in this case study is 1 MJ of energy out from the combustion of HVO fuel in a diesel engine of a heavy-duty truck (EURO V). The assessments according to the PEF, EPD and RED II framework were done by using the same inventory data. The UCO was assumed to consist of 50% rapeseed oil and 50% palm oil. It was collected and treated in Sweden by a company located in Norrköping. The collection of UCO was assumed to be decentralized, meaning that the UCO was collected door-to-door. It was also assumed that the UCO collection was done by truck within the region Götaland and Svealand (up to Östersund) and that 50% of the UCO could be collected in Stockholm region. The collection distance was estimated to be 374 km.

The collected UCO was then transported back to Norrköping where the refinery is located. The UCO was treated and transported to the HVO production plant in Gothenburg assuming a distance of 312 km.

Hydrogen is an important raw material during HVO production. It can be produced by different methods. In this study, the hydrogen was assumed to be produced on site through steam reformation using natural gas as feedstock. The emissions from hydrogen production were obtained from the European Commission's standard values for emission factors of hydrogen for HVO production (European Commission, 2020).

Inventory data on HVO production was provided by Preem where the input and output were estimated based on the composition of the vegetable oil. As mentioned, the studied UCO consists of 50% rapeseed oil and 50% palm oil. The inventory data is shown in Table 3.

Table 3 Inventory data used to model the case study on HVO from used cooking oil (UCO).

HVO production	Quantity	Unit
Inputs		
Used rapeseed oil	0.5	t
Used palm oil	0.5	t
Hydrogen, H_2	0.03	t
Electricity	14	kWh
Fuel gas (from by-products)	270	MJ
Outputs		
HVO	0.85	t
Propane	0.05	t
Methane	0.003	t
Carbon dioxide	0.022	t
Water	0.11	t
Steam surplus	0.06	t

It was assumed that subsequent steps such as isomerization and cracking to improve the quality of the HVO, contribute with less than 1% to the total environmental impact and were therefore excluded from the assessment. The 1% cut-off rule is the same for the PEF and EPD framework.

The co-products that are obtained during the HVO production process are propane, methane, and excess of steam. Propane can be sold on the market but in this study, it was assumed that all propane and methane are used internally as fuel gas.

HVO is transported from the biorefinery by ship to 5 depots in Sweden with an average distance of 521 km and then distributed by truck to filling stations within a radius of 50 km.

The emission factors from the combustion of 1 MJ HVO in a heavy-duty truck class EURO V were obtained from Hallberg et.al (2013).

3.2.1 Multifunctional processes

The PEF, EPD and RED II frameworks suggest different approaches for handling multifunctional processes. In this study, the HVO is a multifunctional process where three additional products are generated: propane, methane, and surplus of steam. Since it was assumed that propane and methane are used within the process, the only co-product is then steam.

The substitution approach was used for the PEF and RED II methods. The latter states that substitution is appropriate for the purpose of policy analysis. In this case, the excess steam is assumed to substitute steam produced in a boiler that was fuelled by natural gas. The avoided use of natural gas led to an emission reduction of 10.2 kg CO_2 per ton UCO (Jogner & Nojpanya, 2021).

For the EPD model allocation based on physical relationships was applied. The chosen physical relationship is energy value which can be indicated by the lower heating value. The lower heating values of HVO and steam is 44.1 MJ/kg and 2.74 MJ/kg respectively. This gives the HVO an allocation factor of 0.94.

3.2.2 Rules for material recycling, reuse, and energy recovery

Since UCO is used as feedstock to produce HVO, the product system involves material/waste recycling. The EPD and RED II framework consider the UCO as waste, while the PEF framework considers it as a secondary material.

For the RED II approach, the UCO which is considered as waste bears no emissions from the previous life cycle up to the point where waste is collected. Hence, a cut-off is applied similarity to the EPD model. However, in the RED II model, the collection of the UCO is included.

For the EPD calculation, environmental impact from using UCO is accounted after the point at which the UCO has its lowest market value i.e., when it is discarded at a collection site. Since a decentralized collection system was assumed, the collection site in this case would refer to the gate of the waste collector i.e., the company that collects the UCO to be treated. This means that the life cycle before UCO is treated is excluded from the system.

The approach adopted in PEF for handling recycled materials is more complicated. Applying the material part of the CFF (see Chapter 2 for the complete formula), the environmental impact of the UCO can be calculated according to the obtained equation:

$$0.5E_{rec} + 0.5E_v \frac{Q_{sin}}{Q_p}$$

The CFF equation above was obtained as R1 equals to 1 (i.e., no virgin material is used as feedstock in the process) and A per default is 0.5. The Erec refers to the emissions from the collection and pre-treatment of the UCO so that it can be used as feedstock in the HVO production process. The Ev factor refers to the emissions and resources used during the acquisition and pre-processing of virgin material. It has become apparent that the definition of the Ev can be interpreted in several ways. In the study done by Jogner and Nojpanya (2021), the Ev factor is interpreted as the upstream burden of the UCO i.e., the virgin cooking oil. However, after some internal discussions and expert consultation, this interpretation was disregarded, and the PEF result was revised. The Ev factor was instead interpreted as the virgin material which could have been used to produce HVO. In other words, Ev represent the emissions and resources used to produce any conventional primary material that can be used to produce HVO. Since HVO can be produced from different type of oil and fats, the choice of the primary material that can be used to estimate the Ev factor is not clear. Despite the wide range of choices, rapeseed oil and palm oil seem to be reasonable alternatives. The reason for selecting both types of vegetable oils instead of one, is because the choice of the primary material can influence the result and that an average value should be used to counter the risk of being over- or underestimated.

The choice of primary material in turn affects the quality ratio Q_{sin}/Q_p. Q_{sin} refers to the quality of the secondary material at the point of substitution and Q_p is the quality of the ingoing secondary material at the point of substitution. The quality of the primary and secondary material can be indicated by market prices.

The point of substitution is placed before the HVO production, meaning that the UCO is used as a feedstock to substitute virgin vegetable oil. Q_{sin} was then interpreted as the price of the ingoing secondary material which is the UCO. The Qp was interpreted as the price of the primary material i.e., the price of rapeseed oil and palm oil. In the calculation, the factor $0.5E_v \frac{Q_{sin}}{Q_p}$ was obtained by assuming the emissions from 50% rapeseed oil and 50% palm oil. The price of the UCO used in the calculation was based on the average price in August 2021 (Greenea, 2021). The obtained UCO price was 1302 USD/tonne UCO where the currency conversion rate is 1 EUR = 1.18 USD (Riksbanken, 2021). For rapeseed oil and palm oil, the price was also taken as an average value during August 2021. The obtained price was 1498 USD/tonne for rapeseed oil and 1236 USD/tonne for palm oil (Neste, 2021). The environmental impact of the UCO was then calculated as followed:

$$E_{UCO} = 0.5Erec + 0.5 * \left(\left(E_{v,RSO/MJ\ HVO} \times \frac{Q_{sin,UCO}}{Q_{p,RSO}}\right) + \left(E_{v,PO/MJ\ HVO} \times \frac{Q_{sin,UCO}}{Q_{p,PO}}\right)\right)$$

Where RSO denotes rapeseed oil and PO denotes palm oil. The Ev is expressed as the impact of each vegetable oil that would be needed for 1 MJ HVO. The CFF specifies that for price ratio higher than one is to be set to 1. This applied to the price ratio between the UCO and palm oil.

When the CFF is calculated and obtained in terms of GWP100, the result was then added to the GWP for the HVO production and the rest of the downstream processes.

3.3 RESULTS AND DISCUSSION

The results for the environmental impact of HVO using the RED II, EPD and PEF frameworks are shown in Figure 4. Figure 4 also shows the result from the sensitivity analysis performed on the PEF model where UCO consisted of different types of oils. The results of the sensitivity analysis are discussed later in this section.

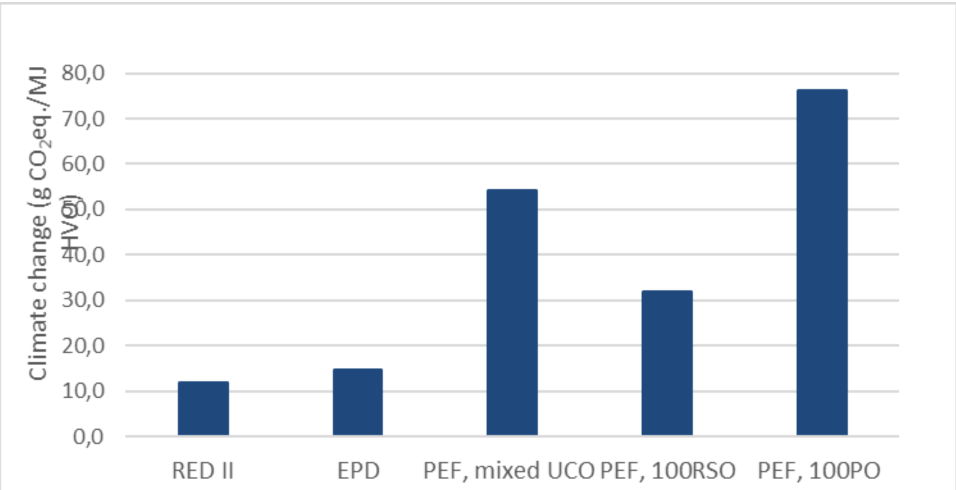

Figure 4. Impact on climate change of HVO from used cooking oil (UCO) using the RED II, EPD and PEF frameworks.

Figure 4 shows that the PEF framework results in the highest impact of 54.1 g CO_2 eq./MJ HVO, compared to the other two frameworks. The lowest impact of 11.9 g CO_2 eq./MJ was obtained when the RED II framework was applied.

The difference in the results is mainly due to the discrepancy between the three allocation approaches applied when it comes to recycling, reuse or recovery of material and energy in the studied system. EPD and RED II apply a “cut-off approach” although due to different motivations behind this choice, different cut-off points are applied. EPD sets the cut-off at the point where waste has its lowest value, to distinguish the life cycle of the primary and secondary material (according to the EPD International’s GPI version 3.01), while RED II excludes all emissions up to the process of waste collection.

PEF uses the CFF to calculate the burden and benefit of using secondary material. The E_v parameter, shows that PEF allocates emissions from the production of the avoided primary material to the UCO. This can be considered as burden to the secondary material. Allocating burden to the secondary material is to prevent double counting. HVO gets a credit from the use of recycled material (UCO) instead of virgin. However, not all burden from Ev is allocated to UCO as there are parameters such as the A factor, R1 and price ratio (Qsin/Qp), which determine the magnitude of this burden. For example, in this case study, the price ratio was a determining factor for how much the burden from the virgin oil is to be allocated to the UCO. If the price of the secondary is higher than the primary material, then the price ratio will be small, and the burden will be lower. For the case of HVO, the price of UCO is lower than the rapeseed oil but higher than the palm oil. This makes the price ratio of the palm oil become higher than that of the rapeseed oil. Thus, more share of the impact from the cultivation and production of palm oil being allocated to the UCO.

The effect of having different approaches in handling the use of waste or secondary material is clearly seen in the case of PEF and RED II where their system boundaries are virtually the same, but the obtained results differ.

In addition, the interpretation of the E_v factor gives a degree of freedom for the PEF practitioner to choose which primary material to be substituted. To investigate the effect of this, a sensitivity analysis was conducted. As shown in Figure 4 the environmental impact of HVO assessed by the PEF framework is highly sensitive to the choice of avoided primary material as the E_v value (and the price ratio) is affected. When 100% palm oil is assumed, the result increases to 76 gCO_2 eq./MJ which correspond to an increase of 41%. With 100% rapeseed oil, the impact is reduced to 32 gCO_2 eq./MJ which correspond to a decrease by 41%.

Looking at RED II, the GHG emissions savings of the UCO-based HVO compared to a fossil fuel (94 g CO_2 eq./MJ) is 87% (well above the current targets set in RED II). However, if the PEF framework is used instead, then the GHG emissions saving is reduced to 43%. This clearly shows that the choice of LCA methodology influences the environmental performance of a fuel thus influencing also decisions related to policy making and climate targets.

The result following the EPD framework is 14.7 gCO_2 eq./MJ which lies between REDI I and PEF results. This is reasonable as their allocation approach for recycling is similar. The EPD framework is based on the attributional LCA approach where substitution is not allowed. This means that the choice of allocation approaches for multifunctional processes is limited compared the other two frameworks.

In terms of documentation, only a general guideline of the PEF and EPD framework could be used as specific rules for biofuels are not available, unlike the RED II framework which is made specifically for biofuels. Hence methodological choices according to PEF and EPD can be interpreted differently by different actors. The interpretation of CFF and thereby the choice of Ev is a clear example, as the PEF practitioner may be able to influence the results by choosing a primary material that has a low impact.

4 BIOGAS – BIOMETHANE

This case study investigates the environmental impact of biomethane produced from biogas via anaerobic digestion of municipal food waste (household waste). The reference flow in the study is 1 MJ of biomethane. The value chain includes the following steps:

- Food production
- Collection of food waste from households
- Transport of food waste to biogas plant
- Pre-treatment of food waste
- Anaerobic digestion of food waste to biogas and digestate
- Upgrade of biogas to vehicle fuel (biomethane)
- Distribution of biomethane to gas station
- Combustion of biomethane in a passenger car

The case study investigates the environmental burdens of a fictive system based on a combination of literature data and data for actual plants. We assume the data used in this study to be representative for a Swedish biogas plant in which food waste is co-digested with other substrates. However, the here studied value chain only includes the food waste.

4.1 SYSTEM BOUNDARIES

Figure 5 shows the system boundaries in relation to the different methods applied to the case study on biomethane production.

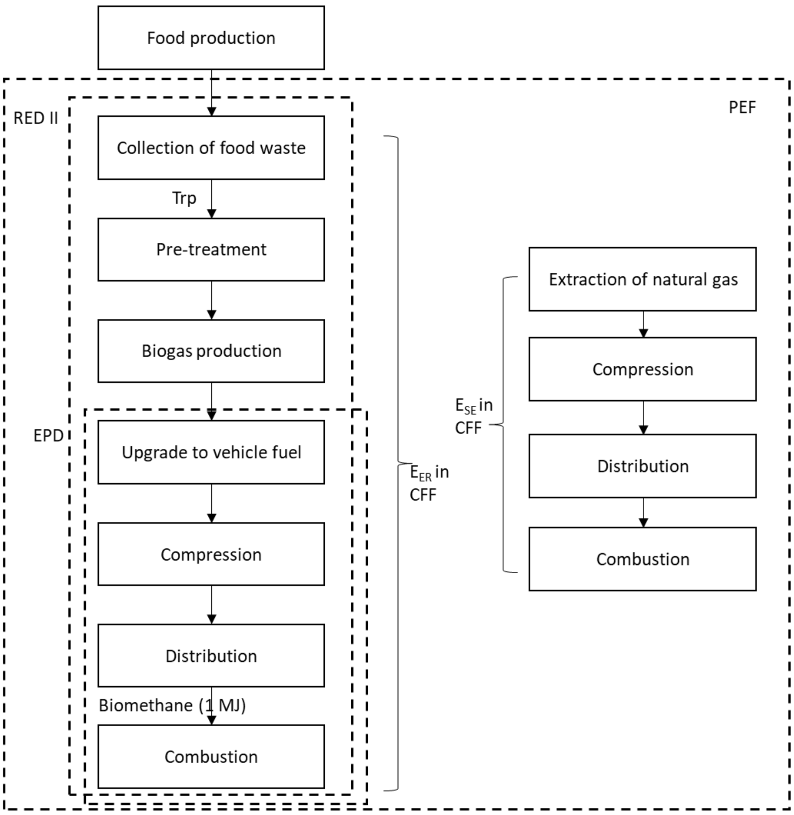

Figure 5. System boundaries in relation to the methods applied; RED II, EPD and PEF.

The three methods resulted in quite different system boundaries, described below. One aspect that affects the systems greatly is how the methods determine which parts of the value chain should be assigned to the food system, and which parts should be assigned to the biogas/biomethane system.

In RED II, the methodology for calculating the impact of biofuels is described in Annex V of the directive. The greenhouse gases are calculated according to the following equation:

$$\mathbf{E = e(ec) + e(l) + e(p) + e(td) + e(u) - e(sca) – e(ccs) – e(ccr)}$$

In the case of biogas from food waste, e(ec) and e(l) are zero since food waste is a waste and thus all upstream emissions are allocated to the food system. Also, e(sca) is set to zero since the system does not affect the agricultural practices as are e(ccs) and e(ccr) since there is no CCS or CCU in the system.

E(p) includes the emissions caused by pre-treatment, digestion and upgrading and storage of digestate at the biogas plant. These emissions are caused by the use of energy as well as by leakage of methane. E(td) includes the emissions from collecting the food waste and the distribution of biogas to gas stations.

As there currently are no PCR for biogas production within EPD International, the broader set rules in the General Programme Instructions (GPI) were interpreted and applied. This year, a new version of the GPI 4.0 was published (EPD International, 2021), which means that we now are in a transition period where both the new and the older GPI (3.01) are valid. The EPD system follows the polluter pays allocation method, which means that the generator of the waste shall carry the full environmental burden until the end-of-waste stage is reached. According to GPI 3.01, this point is defined when the waste has its lowest market value (EPD International, 2019). In GPI 4.0 the point of end-of-waste is defined when a number of criteria are fulfilled (EPD International, 2021).

As mentioned, there are no existing PCRs for biogas for vehicle fuel. However, there is a PCR for electricity generation which covers electricity generation using biogas. This PCRs states that for biogas produced from waste resources, the burdens of the digestion plant shall be allocated to the waste generator, whereas processes to convert the biogas into energy shall be allocated to the energy generating system. Based on this we have defined the system boundary as displayed in Figure 5. The assessed product system includes biogas upgrading, compression of biogas, transportation, and combustion in the vehicle. According to the GPIs, the product system shall be divided into the life cycle stages upstream, core and downstream. As the feedstock in this case is a waste, we suggest that this assessment doesn't include upstream processes. The core processes include the process that the biogas producing company has a direct influence over, i.e., upgrade and compression, and downstream includes distribution (transportation) and combustion.

The PEF 6.3 guidance is used, since no PEFCR exists for biofuels. Figure 5 shows the system boundary of the biogas using PEF. The reason why the system looks like this is due to the following method rules in the PEF 6.3 guidance:

- In section 7.18.20, it is stated that biogas production should be modelled as energy recovery.
- For recycling and energy recovery, the circular footprint formula (CFF) shall be used, and for energy recovery the default value of factor B is zero.

- PEF6.3 also states that "…the subsequent system shall model its own energy as primary energy".

By using the default value for factor B, all burdens and benefits from the energy recovery are allocated to the waste generator, in this case the food system. This entail that the biogas system shall be modelled as the flow that is substituted in the CFF. Since the energy in the subsequent system, which in our case is the biogas system, shall be modelled as primary energy we assumed that the biogas substitutes natural gas. This means that the biogas system was modelled as the extraction, compression, and distribution of natural gas. The PEF guide doesn't specify whether the combustion should be modelled based on the combustion of biogas or natural gas. Therefore, we show the result both with the combustion of natural gas and biogas, see result section.

4.2 KEY INPUT DATA AND ASSUMPTIONS

The same inventory data have been used in the assessment, independent of method. Primary data sources are Börjesson *et al.* (2016), ecoinvent (Wernet *et al*., 2016), and Sphera (2021). Key inventory data and data sources are provided in Table 4. According to the GPI, residual mix on the market shall be applied if specific information about the electricity mix is missing when using the EPD framework. In a Swedish perspective, this means that Nordic residual electricity mix is most relevant. However, to investigate the importance of this choice we compared the results using Nordic residual mix with the results using Swedish residual electricity mix. For RED II the average consumption electricity mix shall be applied.

Table 4. Inventory data used to model the case study on biogas.

Process step	Quantity	Reference
Collection of food waste at households	7 km average distance between household and biogas plant	Assumed value
Pre-treatment	0.034 MJ/MJ (95 MJ/ton food waste)	Börjesson et al. (2016)
Processing	0.03 MJ electricity/MJ and 0.06 MJ heat/MJ (86 MJ electricity/ton food waste and 174 MJ heat/ton food waste)	Personal communication (Tekniska Verken in Linköping)
Methane losses in processing	Leakage: 0.27% of total CH4-production Flared gas: 1% of total CH4-production	Personal communication
Upgrading, electricity water scrubber	0.026 MJ/MJ (0.9 MJ/Nm3)	Börjesson et al (2016)
Upgrading, methane loss	1.03E-04 kg (5%)	Börjesson et al (2016)
Compression, electricity	0.025 MJ (0.025 kWh/kWh)	Börjesson et al (2016)
Production of natural gas	0.0221 kg (45.2 MJ/kg gas)	
Distribution to gas station	100 km	Assumed distance
Combustion of biogas in car	1 MJ	GWP = 0.19 g CO_2eq (simplified)

4.2.1 Multifunctional processes

RED II applies allocation according to lower heating value (LHV). In the system two products are produced namely biogas and digestate. Digestate is used as a fertilizer and is thus an important product from the system to recover the nutrients in the food waste but since the digestate has a high water content the LHV is 0 and thus all emissions in the system are allocated to the biogas.

4.2.2 Rules for material recycling, reuse, and energy recovery

Both RED II and EPD applies cut-off method for allocation of waste, while PEF uses the CFF. According to PEF guide biogas shall be modelled as energy recovery, and since factor B is 0 by default, all burdens and benefits from the energy recovery are allocated to the waste generator, the food system in our case, see Figure 5.

4.3 RESULTS AND DISCUSSION

Figure 6 displays the assessed climate impact of the assessed biogas using the different applied methods.

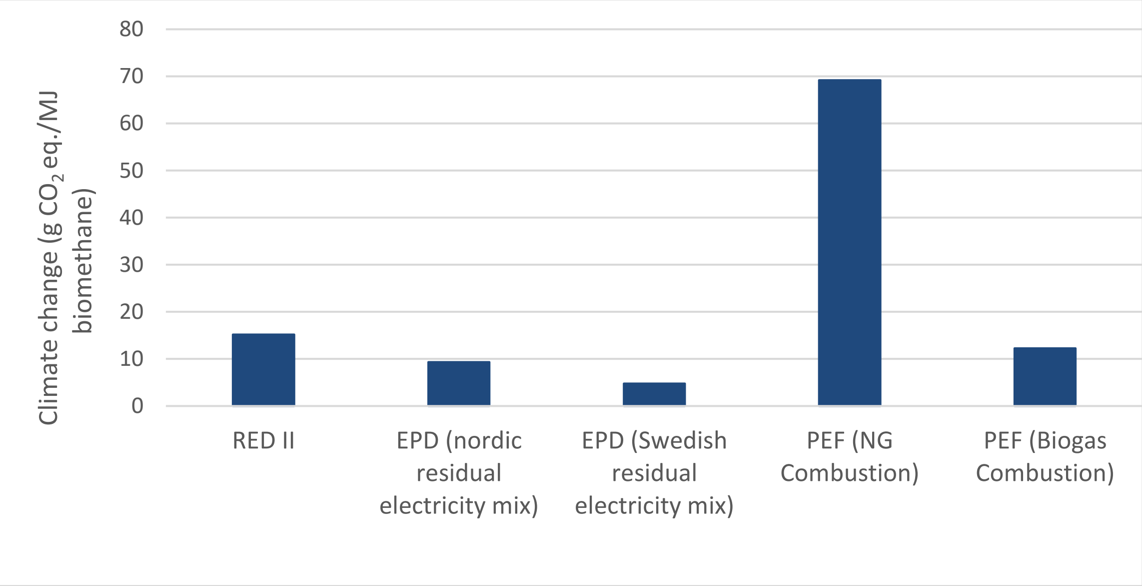

Figure 6. Impact on climate change of biogas from food waste using the three frameworks; RED II, EPD and PEF.

The methods result in quite different system boundaries; this affects the results significantly. The results from the assessment using the EPD framework resulted in the lowest climate impact as shown in Figure 6. The overall climate impact was 9.3 g CO_2eq /MJ fuel with the Nordic residual mix and 4.8 g CO_2eq. /MJ fuel with the Swedish electricity mix. The reason for the low impact for this approach was that the upstream processes from food production to biogas production was not included in the system boundary since these processes were assigned to the waste generating product system. In contrast to the RED II calculation, where collection of food waste, pre-treatment and biogas production were included within the system boundary. This resulted in a total impact of 15.2 g CO_2 eq. /MJ. Largest impact was found for the calculation using PEF methodology and including the combustion of natural gas, 69.2 g CO_2 eq. /MJ. If combustion of biogas was assumed instead the results from the PEF calculation showed a total impact of 12.3 g CO_2 eq./MJ.

From the RED II assessment, the largest emissions were seen for the biogas production including the waste collection and pre-treatment, see Figure 7. In total, the biogas corresponded to an impact reduction of 84% compared to the fossil fuel comparator, which is 94 g CO_2 eq. /MJ. RED II is based on a life cycle perspective but calculating GHGs according to RED II is not equal to performing a full LCA even though it is similar.

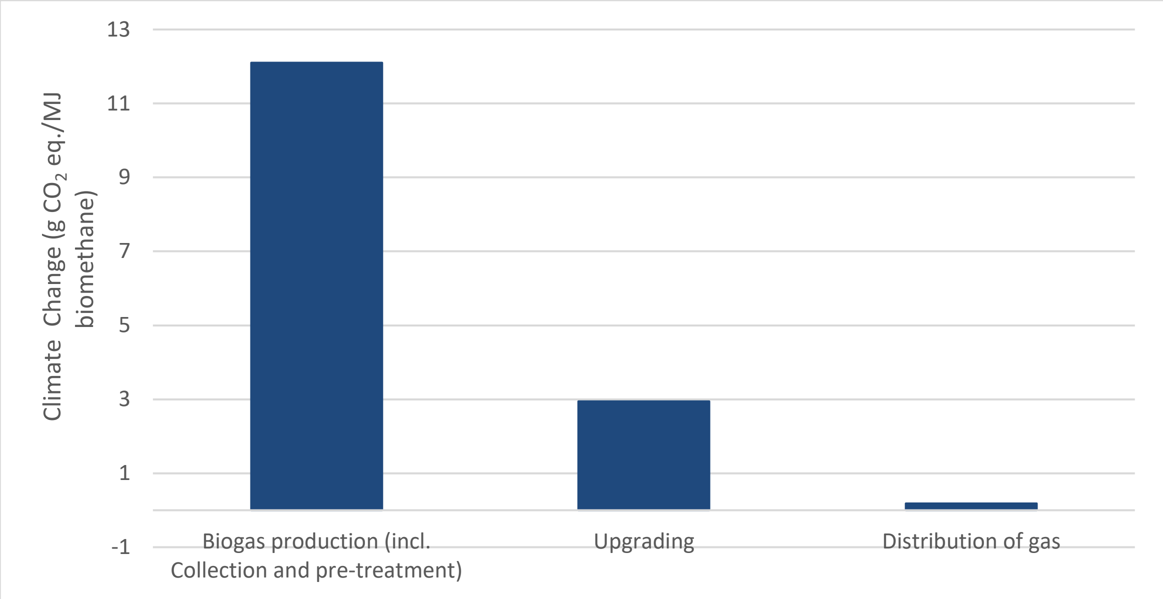

Figure 7. Contribution analysis based on the results from the RED II framework.

The largest impact in the EPD calculation was from the upgrading life cycle stage due to methane loss and electricity use. The second largest impact was modelled for the compression, where most of the impact was attributed to electricity use. The remaining life cycle stages, distribution, and combustion were low, see Figure 8. According to the GPI, GHG (except CO_2) emissions arising from the degradation of food waste shall be included in the assessment. Based on this, only emissions in the form of CH_4 and N_2O were considered in the combustion life cycle stage. Figure 8 also shows that most of the impact was attributed to the core life cycle stage.

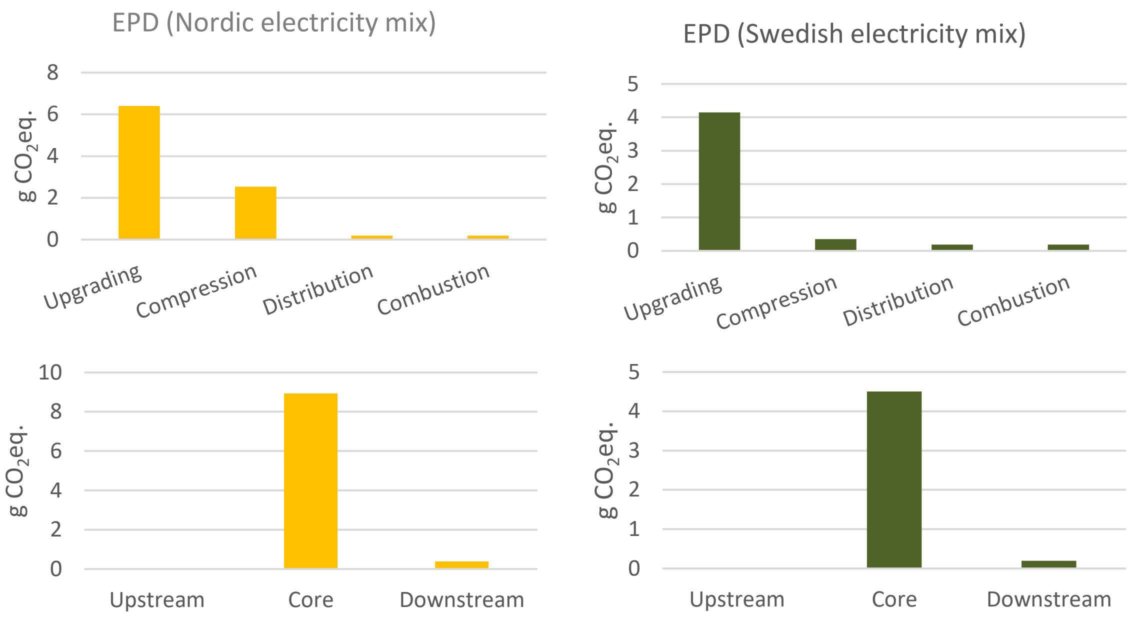

Figure 8. Detailed results from the EPD framework expressed in g CO_2eq /MJ fuel (biomethane). The upper figure displays the climate impact divided into the life cycle processes: Upgrading, Compression, Distribution and Combustion. The lower figures display the climate impact divided into life cycle stages Upstream, Core and Downstream. The figures to the left represent the results applying Nordic residual electricity mix, while the figures to the right show the results with Swedish electricity mix.

The PEF calculation including combustion of natural gas resulted in the highest climate impact (Figure 9). For the case where combustion of biomethane was assumed the climate impact was significantly lower. This "scenario" resulted in a climate impact closer to the other calculations based on the other frameworks, see also Figure 6.

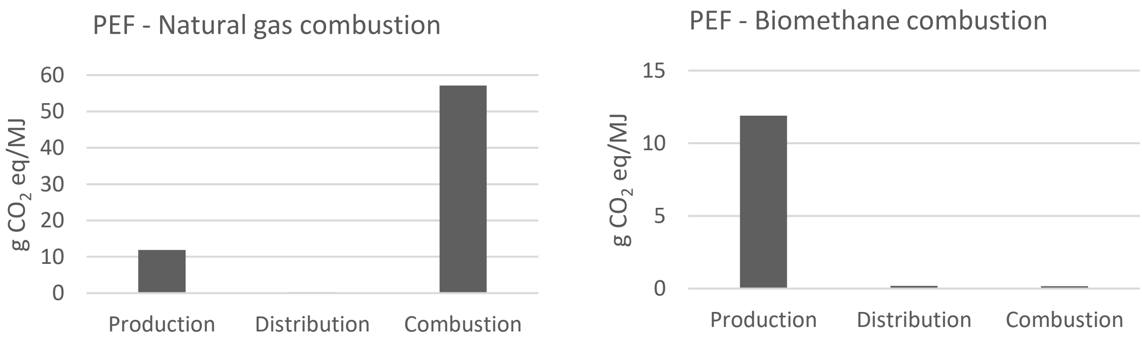

Figure 9. Detailed results from the PEF framework expressed in g CO_2eq /MJ ^{fuel} (biomethane). The right figure shows the impact including combustion of natural gas. The left figure shows the impact when including combustion of biomethane.

5 RAPESEED METHYL ESTER (RME)

RME can be used as a diesel substitute in vehicles. It can be produced via esterification from various vegetable oils and fats which contain triglycerides and fatty acids. Rapeseed oil is the dominant biodiesel feedstock in Europe, accounting for around half of the total production. In this work, we have modelled the cultivation, transport and storage, processing, as well as the direct and indirect land use change phases of the life cycle of the RME.

The cultivation, processing, transport, and storage phases are considered equivalent across the RED II and EPD approaches (where energy allocation is applied), while the PEF approach is applied with substitution to solve co-production. Similarly, direct land-use change (dLUC) is modelled in the same manner between the RED II and EPD approaches, but differently in PEF, as LUC of the marginal crops that balance rapeseed cake used for feed is included. Indirect cultivation of those marginal crops is included only in the PEF approach. Indirect land-use change (iLUC) is only considered in RED and is mutually exclusive to dLUC, for which the factor given in RED is applied.

5.1 SYSTEM BOUNDARIES

Figure 10 shows the system boundaries applied to the case study on RME.

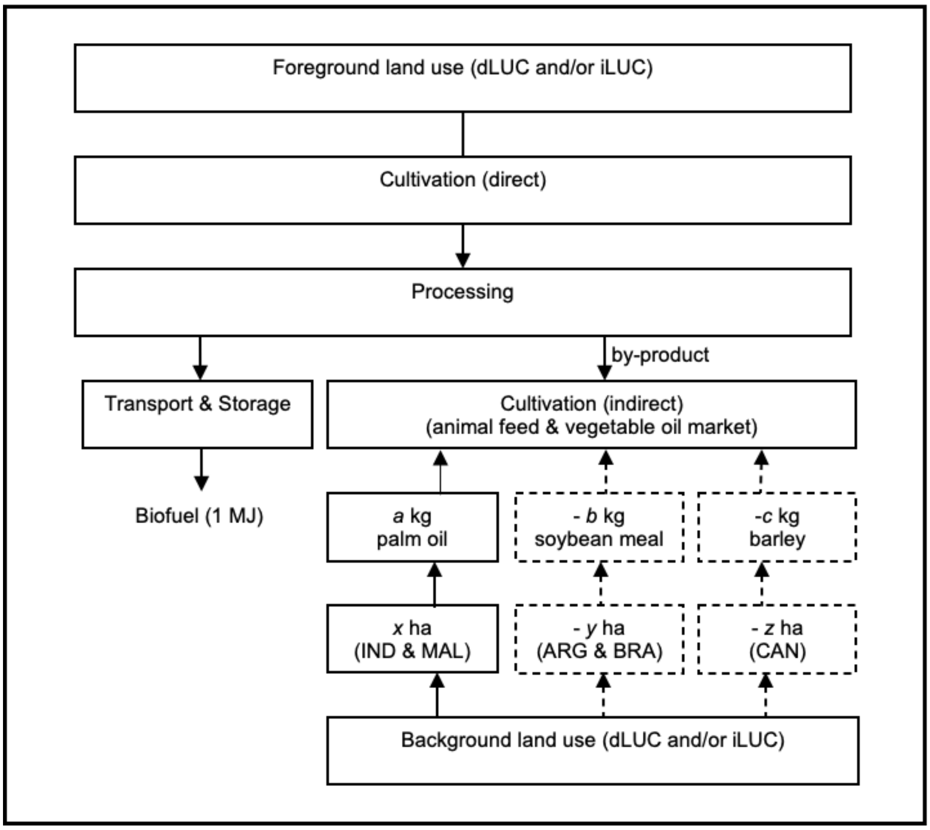

Figure 10. System boundaries in relation to the methods applied; RED II, EPD and PEF. RED II and EPD exclude by products by applying energy allocation, while PEF uses the substitution approach and considers changes in the cultivation and LUC of the marginal crops affected by the rapeseed cake, which is used as an animal feed. As a result, the balancing of the feed and vegetable oil markets is included in PEF.

5.2 KEY INPUT DATA AND ASSUMPTIONS

The updated data from BioGrace found in Brandão et al. (2021) were used as inventory data. See Section 5.0 and Section 5.2.1 for specific methodological choices on co-production.

5.2.1 Multifunctional processes

The extraction of oil from rapeseed results in two co-products: crude vegetable oil and rapeseed cake (which can be used as animal feed). Their respective mass and energy contents give an energy allocation factor of 61.3% and 38.7%, respectively. The processing of rapeseed oil into RME at the esterification stage results in the co-production of RME and glycerol. Applying energy allocation gives a factor of 95.7% and 4.3%, respectively, to RME and glycerol.

5.2.2 Rules for material recycling, reuse, and energy recovery

Not applicable in this case study.

5.3 RESULTS AND DISCUSSION

Figure 11 shows the carbon footprint modelled with the different approaches. The taxing iLUC factor of 55.0 g CO_2 eq./MJ makes RME worse than the fossil-fuel comparator in the RED-iLUC approach (94.0 g CO_2 eq./MJ). In the other approaches, RME is considerably better than fossil diesel, but does not meet the EC target of a minimum of 65% GHG savings relative to fossil diesel from 2021 onwards. The RED-dLUC approach gives a result of 57.2 g CO_2 eq./MJ, while the PEF and EPD approaches give a value of 77.9 and 57.0 g CO_2 eq./MJ, respectively.

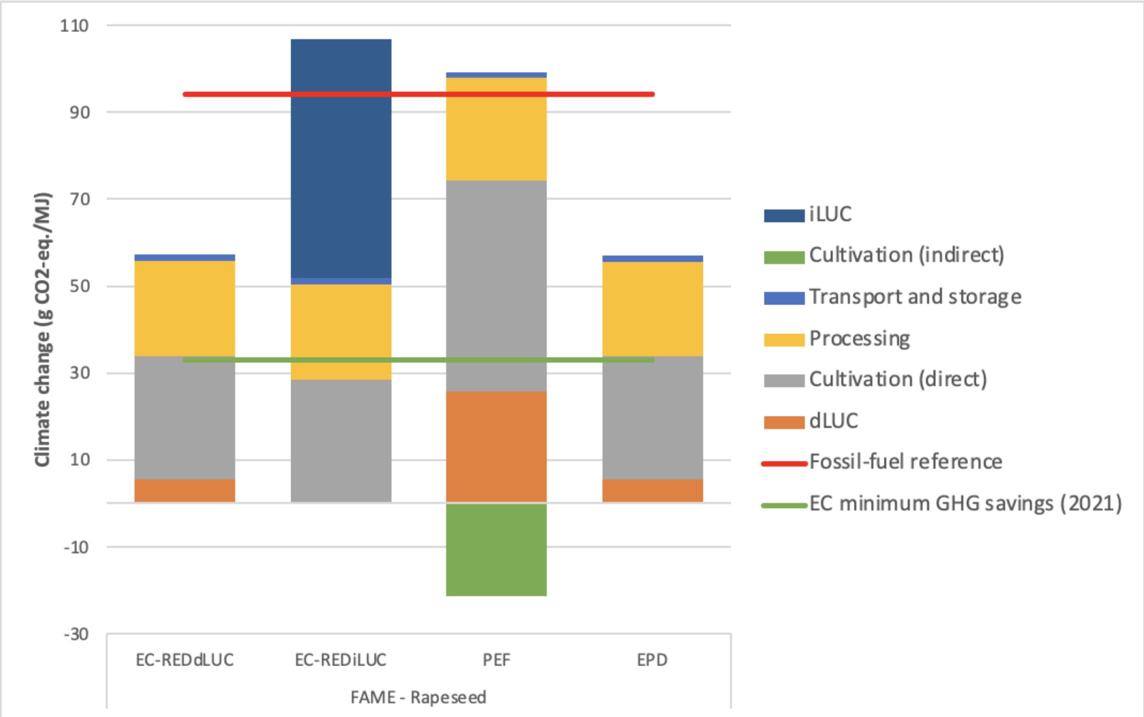

Figure 11. Impact on climate change of RME using the three frameworks; RED II, EPD and PEF.

6 HVO FROM RAPESEED OIL (RSO)

RSO can be used as a diesel substitute in vehicles. It can be produced from various vegetable oils and fats which contain triglycerides and fatty acids. Rapeseed oil is the most common vegetable oil in Europe. We have modelled the cultivation, transport and storage, processing, as well as the direct and indirect land use change phases of the life cycle of the RME.

The cultivation, processing, transport, and storage phases are considered equivalent across the RED II and EPD approaches (energy allocation is applied), while the PEF approach is applied with substitution to solve co-production. Similarly, direct land-use change (dLUC) is modelled in the same manner between the RED II and EPD approaches, but differently in PEF, as LUC of the marginal crops that balance rapeseed cake used for feed is included. Indirect cultivation of those marginal crops is included only in the PEF approach. Indirect land-use change (iLUC) is only considered in RED and is mutually exclusive to dLUC, for which the factor given in RED II is applied.

6.1 SYSTEM BOUNDARIES

Figure 12 shows the system boundaries applied to the case study on HVO from rapeseed oil (RSO).

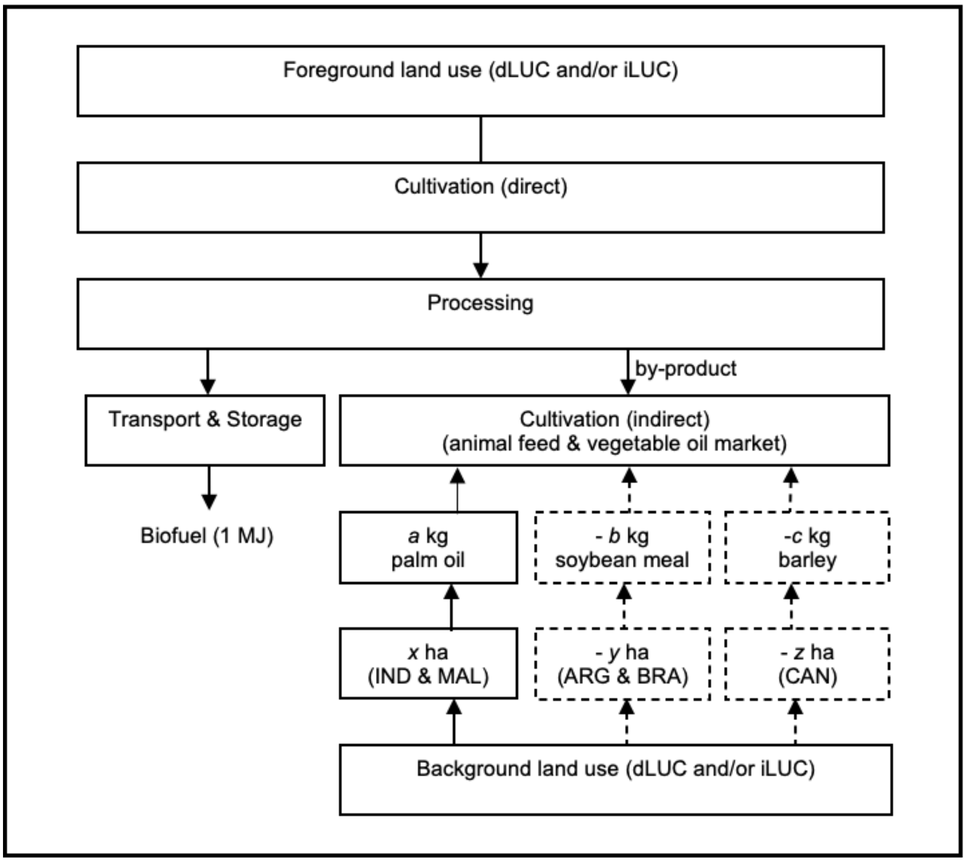

Figure 12. System boundaries in relation to the methods applied; RED II, EPD and PEF. RED II and EPD exclude by products by applying energy allocation, while PEF uses the substitution approach and considers changes in the cultivation and LUC of the marginal crops affected by the rapeseed cake, which is used as an animal feed. As a result, the balancing of the feed and vegetable oil markets is included in PEF.

6.2 KEY INPUT DATA AND ASSUMPTIONS

The updated data from BioGrace found in Brandão et al. (2021) were used as inventory data. See Section 6.0 and Section 6.2.1 for specific methodological choices on co-production.

6.2.1 Multifunctional processes

The extraction of oil from rapeseed results in two co-products: crude vegetable oil and rapeseed cake (which can be used as animal feed). Their respective mass and energy contents give an energy allocation factor of 61.3% and 38.7%, respectively.

6.2.2 Rules for material recycling, reuse, and energy recovery

Not applicable in this case study.

6.3 RESULTS AND DISCUSSION

Figure 13 shows the carbon footprint modelled with the different approaches. The taxing iLUC factor of 55.0 g CO_2 eq./MJ makes RSO worse than the fossil-fuel comparator in the RED-iLUC approach (94.0 g CO_2 eq./MJ). In the other approaches, RSO is considerably better than fossil diesel, but does not meet the EC target of a minimum of 65% GHG savings relative to fossil diesel from 2021 onwards. The RED-dLUC approach gives a result of 49.5 g CO_2 eq./MJ, while the PEF and EPD approaches give a value of 76.9 and 50.5 g CO_2 eq./MJ, respectively.

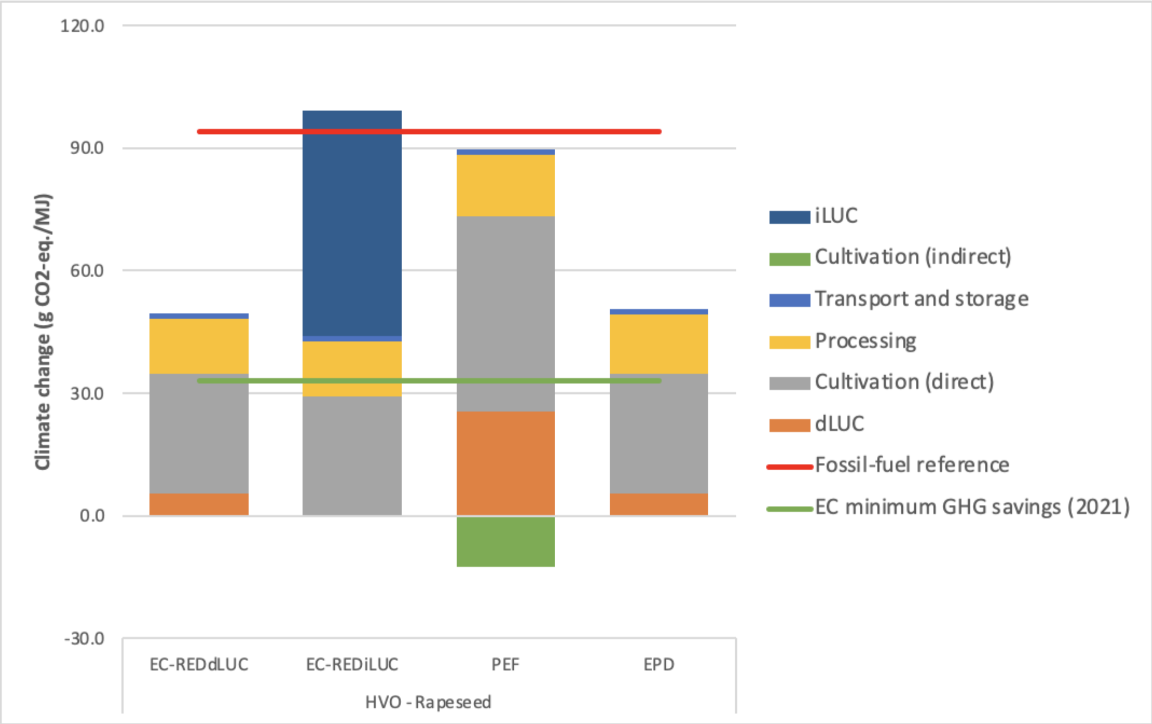

Figure 13. Impact on climate change of RSO using the three frameworks; RED II, EPD and PEF.

7 ETHANOL FROM CORN

Ethanol is a gasoline substitute that can be made from sugar and starch crops. Corn is the most common feedstock in the USA. We have modelled the cultivation, transport and storage, processing, as well as the direct and indirect land use change phases of the life cycle of the corn ethanol.

The cultivation, processing, transport, and storage phases are considered equivalent across the RED II and EPD approaches (energy allocation is applied), while the PEF approach is applied with substitution to solve co-production. Similarly, direct land-use change (dLUC) is modelled in the same manner between the RED II and EPD approaches, but differently in PEF, as LUC of the marginal crops that balance dried distillers' grains with solubles (DDGS) used for feed is included. Indirect cultivation of those marginal crops is included only in the PEF approach. Indirect land-use change (iLUC) is only considered in RED II and is mutually exclusive to dLUC, for which the factor given in RED is applied.

7.1 SYSTEM BOUNDARIES

Figure 14 shows the system boundaries applied to the case study on corn ethanol.

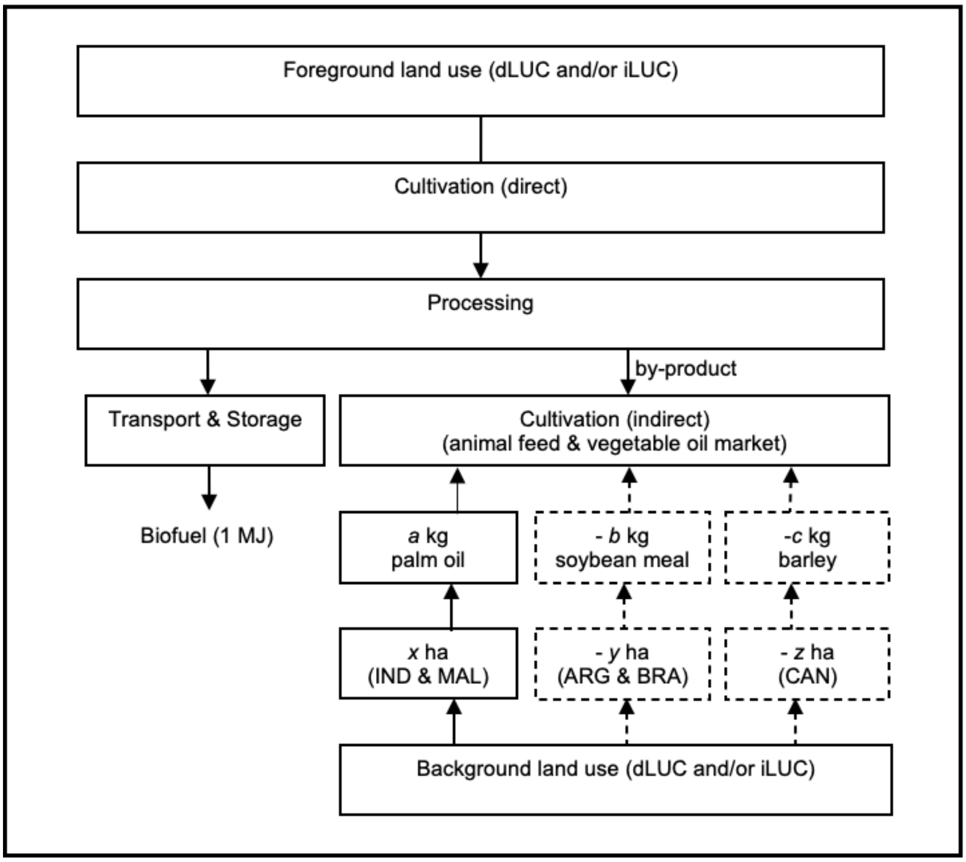

Figure 14. System boundaries in relation to the methods applied; RED II, EPD and PEF. RED II and EPD exclude by products by applying energy allocation, while PEF uses the substitution approach and considers changes in the cultivation and LUC of the marginal crops affected by the DDGS, which is used as an animal feed. As a result, the balancing of the feed and vegetable oil markets is included in PEF.

7.2 KEY INPUT DATA AND ASSUMPTIONS

The updated data from BioGrace found in Brandão et al. (2021) were used as inventory data. See Section 7.0 and Section 7.2.1 for specific methodological choices on co-production.

7.2.1 Multifunctional processes

The processing of corn into ethanol at the ethanol plant results in the co-production of dried distiller's grains with solubles (DDGS). The mass and energy content of the co-products give an allocation factor of 54.6% and 45.4% to ethanol and DDGS, respectively, when allocation by energy is applied.

7.2.2 Rules for material recycling, reuse, and energy recovery

Not applicable in this case study.

7.3 RESULTS AND DISCUSSION

Figure 15 shows the carbon footprint modelled with the different approaches. The lower iLUC factor of 12.0 g CO_2 eq./MJ for starch crops makes corn ethanol (63.5 g CO_2 eq./MJ) better than the fossil-fuel comparator in the RED-iLUC approach (94.0 g CO_2 eq./MJ). In the other approaches, corn ethanol is also considerably better than fossil gasoline, but also does not meet the EC target of a minimum of 65% GHG savings relative to fossil fuels from 2021 onwards. The RED-dLUC approach gives a result of 50.9 g CO_2 eq./MJ, while the PEF and EPD approaches give a value of 59.3 and 50.9 g CO_2 eq./MJ, respectively.

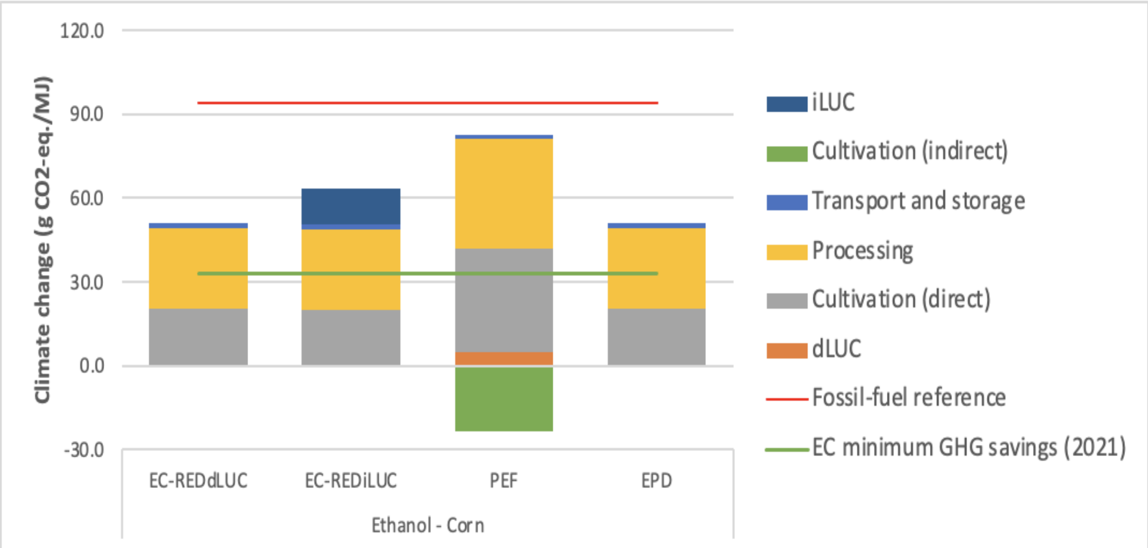

Figure 15. Impact on climate change of corn ethanol using the three frameworks; RED II, EPD and PEF.

8 ETHANOL FROM BREAD WASTE AND RESIDUES

This case study investigates the environmental impact of ethanol produced from food waste. Food waste such as residues from bakeries, breweries, and surplus bread and biowaste from stores are high in starches and sugars, which makes them a suitable feedstock for production ethanol. An existing production plant in Gothenburg has served as an example to illustrate the supply chain and associated processes considered for this specific pathway. The studied value chain included the stages of:

- Food waste collection and transport to the ethanol production facility
- Ethanol production via saccharification and fermentation
- Ethanol dehydration and distillation
- Distribution of ethanol to fuel stations
- Ethanol combustion in a passenger car

The production of ethanol can be divided into three steps: enzymatic hydrolysis, fermentation, and distillation. During enzymatic hydrolysis, carbohydrates such as starch and cellulose are broken down into sugars. To do this, enzymes such as amylase are needed. During fermentation, sugars are converted to ethanol and carbon dioxide (CO_2) using yeast. The final step is distillation where yeast solids and water are removed. This process also produces drank as by-product. Drank can be further used for animal feed or as a feedstock for biogas production.

The produced ethanol is distributed via pipelines to the refinery tanks. Ethanol is then mixed with gasoline (e.g., E10, which contains 10% ethanol) before it's transported from the refinery by ship and/or truck. For the shake of simplicity and comparability to the other fuels presented in this work a fuel of 100% ethanol is assumed for the use stage in all three frameworks although this is not common at least in the European markets.

Modelling of the ethanol production pathway have been performed in the LCA software GaBi (Sphera, 2021).

8.1 SYSTEM BOUNDARIES

The system boundaries applied, and processes included in the assessment are illustrated in the simplified flowchart below.

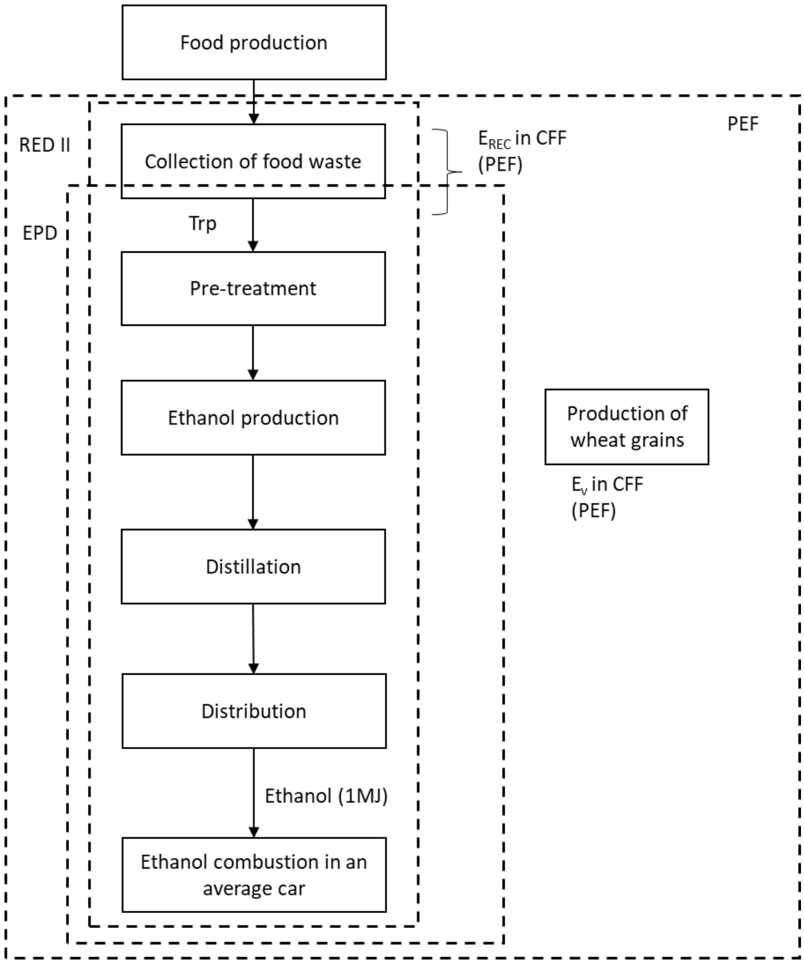

Figure 16. System boundaries in relation to the methods applied; RED II, EPD and PEF.

Ethanol from bread is considered an advanced biofuel according to RED II, Part A in Annex IX of the Directive (EU) 2018/2001 produced from industrial residues. As further stated in Part C §18 in the case of biofuels and bioliquids, all co-products shall be considered for the purposes of the GHG emissions calculation. However, no emissions shall be allocated to wastes and residues. For this reason, no upstream emissions are attributed to the feedstock used in this case study. The system boundary for ethanol according to RED II begins with the collection and transport of waste from the bakeries to the ethanol production plant and ends with the combustion of ethanol in an average passenger car.

The EPD system follows the polluter pays (PP) principle, which means that the generator of the waste shall carry the full environmental burden until the end of waste stage is reached. According to GPI 3.01, this point is defined when the waste has its lowest market value or more specific *"…the generator of the waste shall carry the full environmental impact until the point in the product's life cycle at which the waste is transported to a scrapyard or the gate of a waste processing plant (collection site)."* (EPD International, 2019).

In this case study, the majority of bread waste is transported directly to the factory gate. A small share is transported to the company's collection sites and then transported to the fermentation plant. Following the GPI rules, the ethanol production plan shall not carry any environmental impact from the food waste transport prior to the gate of the company. The system boundary can be then considered as gate-to-grave including the stages of internal transport to fermentation plant, processing, refinement and use stage (Figure 16).

According to the EPD life cycle stages division, upstream processes shall include the production of all raw materials and intermediate products used during the ethanol production process. The core process includes the transport of raw materials and auxiliary materials to the ethanol plant, the ethanol production process and impacts generated by the electricity production or fuels burned in the core process, waste treatment processes of manufacturing waste etc. Downstream processes (from gate-to-grave) includes the ethanol distribution and use (i.e., combustion in an average vehicle).

For the PEF estimations, the system boundary of ethanol starts with the collection of bread waste and residues, including internal transports to the fermentation plant, processing, refinement, and use. However, since bread waste is used as feedstock to produce ethanol, the CFF is applied (see a more detailed description below). The use of CFF involves the emissions from primary materials (Ev) that are replaced by the secondary material (bread waste and residues). In this study, the primary material for ethanol is considered to be wheat grains. This leads to a share of the production and transportation of wheat grains being included in the system boundary as well (see also Figure 16).

8.2 KEY INPUT DATA AND ASSUMPTIONS

The material and energy balance in relation to the studied process were obtained from St1 AB who is a member of the project. The data provided are, however, confidential and cannot be displayed in detail in this work. Both material and energy flows were considered for the assessment.

8.2.1 Multifunctional processes

Besides ethanol, drank is produced as co-product, which can be sold for animal feed. Drank can be sold in liquid- (from 8 to 28% dm) and dry form (90% dm). In this specific case study, drank is sold in liquid form with a density of 1000kg/m^3. A dry content of 20% has been assumed for the calculations needed.

RED II suggests allocation according to lower heating value (LHV). As the LHV of liquid drank can be expected to very low, all emissions during ethanol production are first allocated to ethanol. Alternatively, and considering only the dry content of drank, allocation based on LHV can be applied. The LHV of ethanol is 27 MJ/kg. The LHV value for drank on dry basis is 17.5 MJ/kg (Bernesson & Strid, 2011). The allocation factor for ethanol is estimated then to 0.36 indicating that 36% of the impacts from feedstock collection and ethanol production are allocated to ethanol.

According to the GPI hierarchy and when allocation cannot be avoided, allocation based on physical or other relationship can be used instead. In this case allocation based on energy content is considered leading to the same allocation factors as discussed for the RED II framework.

As described earlier the PEF framework has a decision hierarchy which assists in handling multifunctional processes. The first alternative concerns subdivision or system expansion which cannot be applied in this case partly because data separation is not possible and partly because the focus of the study is ethanol and ethanol and other products. The second alternative is allocation. Allocation can be done based on physical relationships where the impacts are partitioned among the main and co-products or by system expansion and direct substitution i.e., by considering subtracting the additional functions related to the co-products from the main system (ethanol production). The latter approach is applied in this case. The drank produced in this process is sold directly as animal feed. Avoided production of soybean meal has been considered as the substituted product based on data from Salil *et al.*, (2010), Bernesson & Strid (2011) and Börjesson *et al.* (2010).

8.2.2 Rules for material recycling, reuse, and energy recovery

According to the EPD and RED II frameworks, wastes shall carry no upstream burden from previous life cycles. Thus, no impact from production of bread is included within the system boundaries. Instead, the system boundaries start with bread and food waste collection.

In the PEF framework, the CFF is applied. The use of CFF involves the emissions from primary materials (Ev). Burdens in relation to the production of primary materials and the factor $(\mathbf{1}-\boldsymbol{R_1})*\boldsymbol{E_V}$ in the original formula is considered as zero, as R_1=1. This is because no primary feedstock enters the production process. The remaining fraction representing burdens and benefits related to secondary materials input is shown in the equation below:

$$\boldsymbol{R_1} * (\boldsymbol{A} * \boldsymbol{E_{REC}} + (\mathbf{1} - \boldsymbol{A}) * \boldsymbol{E_v} * \left(\frac{\boldsymbol{Q_{Sin}}}{\boldsymbol{Q_p}}\right))$$

A factor is assumed 0.5. The environmental impact from wheat grains production and transport (Ev) is estimated based on generic ecoinvent datasets. The factor Erec represents the stages of collection and transport of bread waste as described above. The quality factor $\left(\frac{\boldsymbol{Q_{Sin}}}{\boldsymbol{Q_p}}\right)$ is based on the market price for bread residues vs price from wheat (primary material). The values considered in this work are taken from literature. For bread waste an average price of 1.05 SEK per kg waste is considered (Gmoser et al 2021, Hirschnitz-Garbers 2015) while for wheat the assumed price is 1.85 SEK per kg. The quality factor is in turn 0.56. The impact from feedstock based on the CFF in this case is:

$$\boldsymbol{E} = \mathbf{0.5} * \boldsymbol{E_{REC}} + \mathbf{0.5} * \boldsymbol{E_V} * \mathbf{0.56}$$

8.3 RESULTS AND DISCUSSION

The results obtained when the three frameworks were applied to ethanol production from bread residues are presented in Figure 17. Due to confidentiality only normalized values are shown. The higher impact was obtained when the PEF framework was applied and when energy allocation was assumed for the by-product obtained during ethanol production. When assuming that soybean meal will be substituted by the by-product though, the PEF framework leads to the lowest impact. The results for RED II and EPD are at similar levels with EPD leading to slightly lower impact at the collection stage (less feedstock transports are included in the system boundary) as showed by the contribution analysis in Figure 18. It can noted that only RED II and EPD alternatives are well below the RED II GHG emissions reduction target when compared to the fossil fuel comparator. The emission reduction level in the case of PEF would depend on the allocation approach assumed.

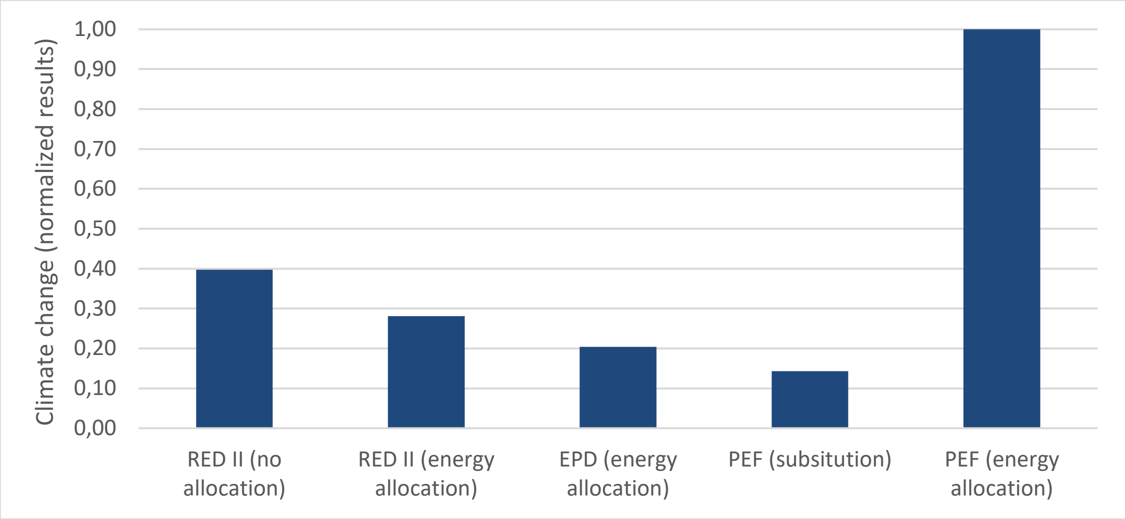

Figure 17. Impact on climate change of ethanol production from bread residues using the three frameworks; RED II, EPD and PEF. Normalized results are displayed indicating the higher and lower values obtained.

The impact from the production stage of ethanol also varies as different electricity mixes are assumed (residual Swedish mix for the case of EPD vs average Swedish mix for the case of RED II). The use phase in all cases leads to no fossil carbon emissions as a fully renewable fuel is assumed in this case. As clearly shown in the contribution analysis the impact from feedstock acquisition in the case of PEF leads to higher impacts mainly due to the fact that a share wheat grain production is attributed to the studied system (Figure 18).

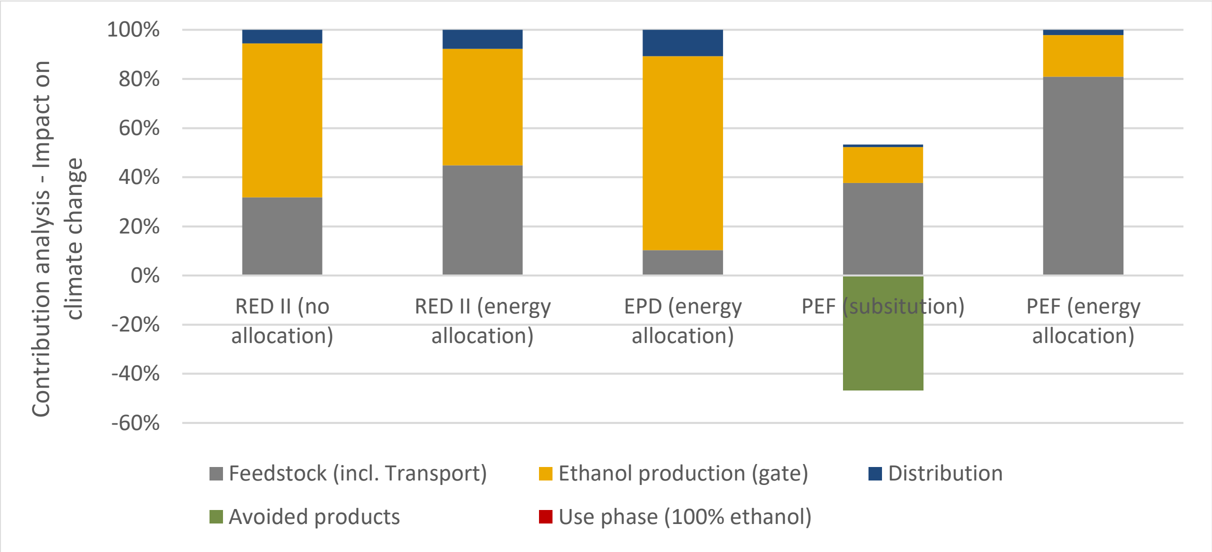

Figure 18. Analysis of the contribution to the impact of climate change of the different processes and life cycle stages of ethanol production and use as estimated based on the three frameworks; RED II, EPD and PEF.

The findings presented above regarding PEF assume that the point of substitution i.e., the point when the recycled material replaces virgin material, occurs at the ethanol plant. For this reason, the factor Ev represents the feedstock that could be used instead of the bread residues. In the absence of a specific PEFCR for renewable fuels multiple interpretations could be valid. Another point of substitution could be identified at the point where advanced ethanol replaces other fuel i.e., at the point where renewable fuel is blended with fossil fuel or even at the point where advanced ethanol replaces first generation ethanol. For the purposes of this study and after communication with PEF helpdesk the original approach i.e., Ev representing primary feedstock is selected.

9 ETHANOL FROM SAWDUST

In this case study, the environmental impact of ethanol from sawdust is studied. Sawdust is a by-product from the sawmill industry. It contains lignocellulose which can be broken down into fermentable sugars. Production concept, currently demonstrated in Finland, was chosen to represent the production processes and supply chain of this cellulosic ethanol. The considered supply chain consists of the following stages:

- Forestry activities
- Sawmill operation and production of sawdust as process residue
- Transport of sawdust to the ethanol plant
- Production of ethanol
- Distribution of ethanol to fuel stations
- Combustion of ethanol in a passenger car

The production of ethanol includes pre-treatment, enzymatic hydrolysis, fermentation, and distillation. Apart from ethanol, the processes also produce by-products: lignin cake, furfural, turpentine and liquified biogas (LBG).

Bioethanol in this case is first transported and mixed with gasoline (in a blend containing 10% ethanol) and then distributed to the filling stations. For the shake of simplicity and comparability to the other fuels presented in this work a fuel of 100% ethanol is considered although this is not common at least in the European market.

Modelling of the ethanol production pathway have been performed in the LCA software GaBi (Sphera, 2021).

9.1 SYSTEM BOUNDARIES

The system boundaries applied, and processes included in this case study are illustrated in the simplified flowchart below.

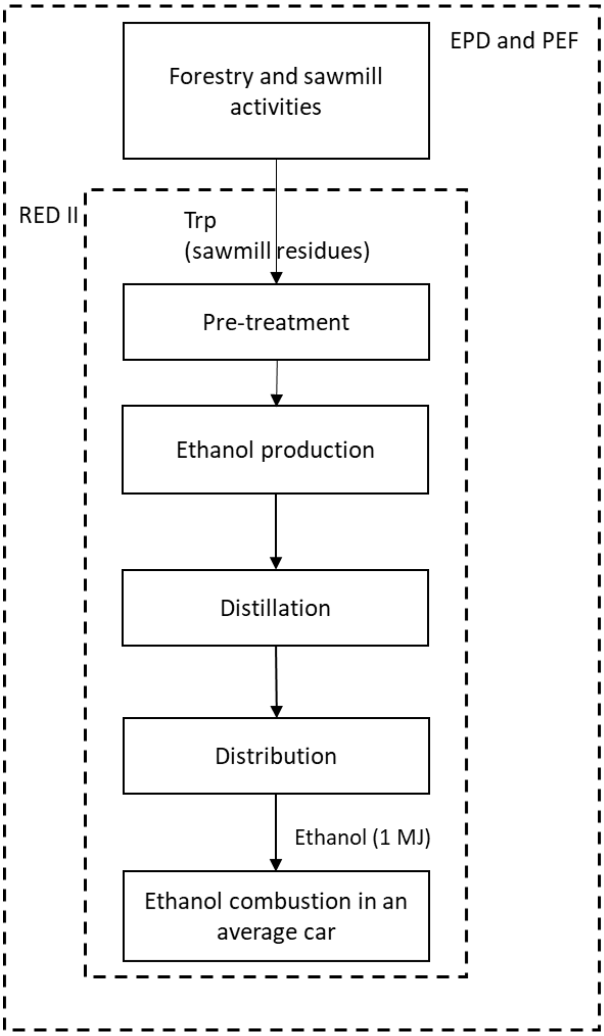

Figure 19. System boundaries in relation to the methods applied; RED II, EPD and PEF.

Ethanol from sawdust is considered an advanced biofuel according to Part A in Annex IX of the Directive (EU) 2018/2001 produced from industrial residues. As further stated in Part C §18 in the case of biofuels and bioliquids, all co-products shall be taken into account for the purposes of the GHG emissions calculation. However, no emissions shall be allocated to wastes and residues. For this reason, no upstream emissions (i.e., from forestry, wood acquisition and processing) are attributed to the feedstock used in this case study.

The life cycle stages that are included in the system boundary when it comes to the RED II framework start from the transport of sawdust to the ethanol plant and ends at the combustion of the ethanol blend in a passenger car (shown in Figure 19). For the EPD framework a cradle-to-grave approach is applied. As sawdust is considered a by-product with an economic value, a share of the impacts from upstream activities (i.e., forestry and sawmill activities) shall be allocated to sawdust. The system boundary of ethanol according to the EPD-framework would therefore include the production and transportation of sawdust to the ethanol plant (upstream), ethanol production (core), as well as the distribution and combustion stage of the ethanol in a vehicle (downstream processes). Similarly to EPD, PEF also applies a cradle-to-grave approach including all processes considered above.

9.2 KEY INPUT DATA AND ASSUMPTIONS

The material and energy balance in relation to the studied process were obtained from St1 AB who is a member of the project. The data provided are, however, confidential and cannot be displayed in detail in this work. Both material and energy flows were included in the assessment.

9.2.1 Multifunctional processes

As discussed above the first allocation point of this case study occurs at the sawmill where sawdust is obtained as by-product along with the main product sawn timber. Due to lack of specific data, generic datasets and previously published EPDs were used as proxy for this process. Two EPDs on sawn timber were identified one published from the finish program operator RTS conducted by the Finish Sawmill Association[8] and one published from EPD International by Swedish wood[9]. In both cases the results are presented per m3 sawn timber that is the main product of the sawmill process resulting in a total impact of about 30 kg CO_2-eq. per m^3 sawn and dried timber (or 58 g CO_2-eq. per kg sawn and dried wood). In the Swedish EPD 15% of the impact at the sawmill is attributed to by-products such as sawdust while more than 80% to the sawn timber. Although this is a very rough assumptions the same allocation factor is used here to model the upstream processes. The same assumption has been done in the case of PEF. This allocation point is out of the scope of RED II therefore not affecting the result.

The second point where a multifunctional process is identified is at the core ethanol production process. The process produces among others lignin, furfural, turpentine and liquified biogas (LBG) as by-products leading to the second allocation point.

For RED II and EPD allocation according to the lower heating value (LHV) of the by-products was applied. The LHV considered are: lignin cake (47% DM) = 10.2 MJ/kg, furfural= 24,2 MJ/kg, turpentine= 41.3 MJ/kg , liquified biogas (LBG) = 50 MJ/kg. The allocation factor for ethanol is 27%.

For the case of PEF, both energy-based allocation as well as system expansion and substitution were applied. For the by-products obtained different substitution scenarios could be identified replacing intermediate chemicals, fuels or materials. Due to lack of specific data in this case, and the high uncertainties entailed, furfural and turpentine are assumed to replace an average organic chemical while LBG is replacing liquified natural gas. Lignin can be used on multiple applications thus different substitution alternatives can be identified (Hermansson *et al.*, 2020). In this work lignin is assumed to be burned to produce electricity (at 40% efficiency) substituting finish electricity at the grid.

9.2.2 Rules for material recycling, reuse, and energy recovery

Not applicable in this case study.

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[8] https://cer.rts.fi/wp-content/uploads/rts-epd_124-21_sahateollisuus_sawn-and-planed-lumber.pdf

[9] https://portal.environdec.com/api/api/v1/EPDLibrary/Files/8d0a16a5-41dd-49e4-9fcf-08d8f8b9d146/Data

9.3 RESULTS AND DISCUSSION

The results obtained when the three frameworks were applied to ethanol production from sawdust are presented in Figure 20. Again, the normalized values are shown.

The results in this case show coherence when the same allocation approach is used and despite the slightly different system boundaries considered. RED II leads to the lowest impact as no upstream emissions are allocated to saw dust production (apart from collection). PEF leads to the lower impact when the substitution approach is considered while it may also lead to the highest impact when energy allocation is applied.

It can noted that all values are well below the RED II GHG emissions reduction target when compared to the fossil fuel comparator a result that is also in line with previous studies of similar systems (Haus *et al*. 2020).

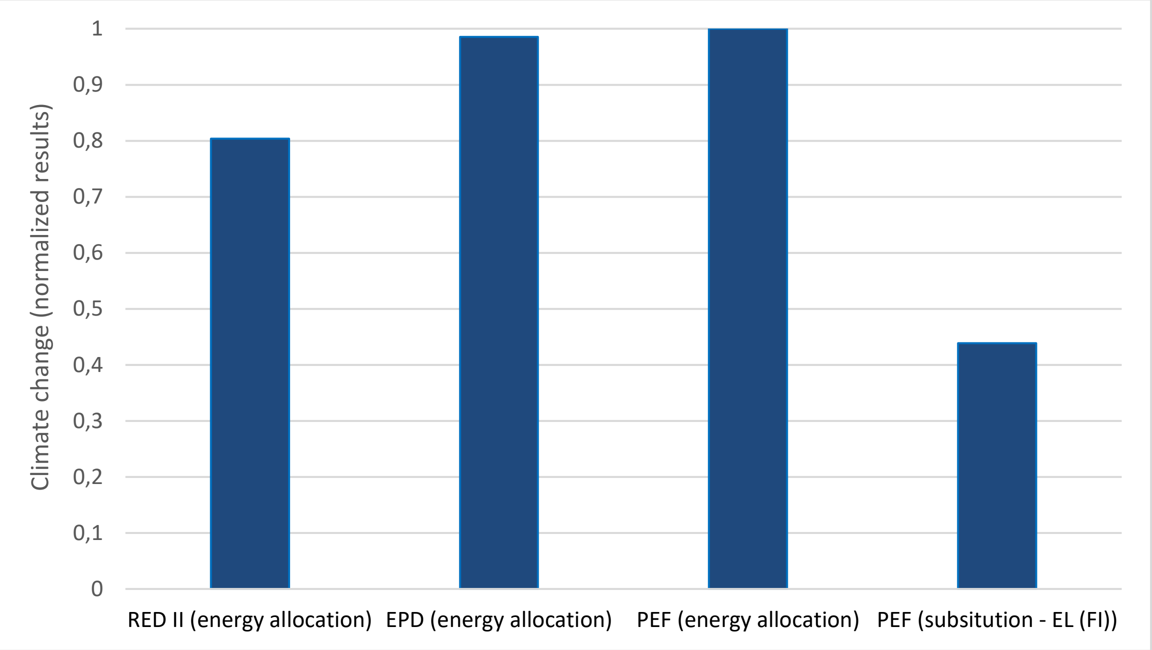

Figure 20. Impact on climate change of ethanol production from sawdust using the three frameworks; RED II, EPD and PEF. Normalized results are displayed indicating the higher and lower values obtained.

The contribution of the different processes and life cycle stages to the total impact are shown in Figure 21. The ethanol production step dominates the impact on climate change mainly due to the resources and materials used in the process (such as process chemicals, enzymes etc). The impact from feedstock acquisition varies as a result of different boundaries considered. It should be noted that only the impact of 100% renewable ethanol is presented here, thus no impact from the use phase is shown.

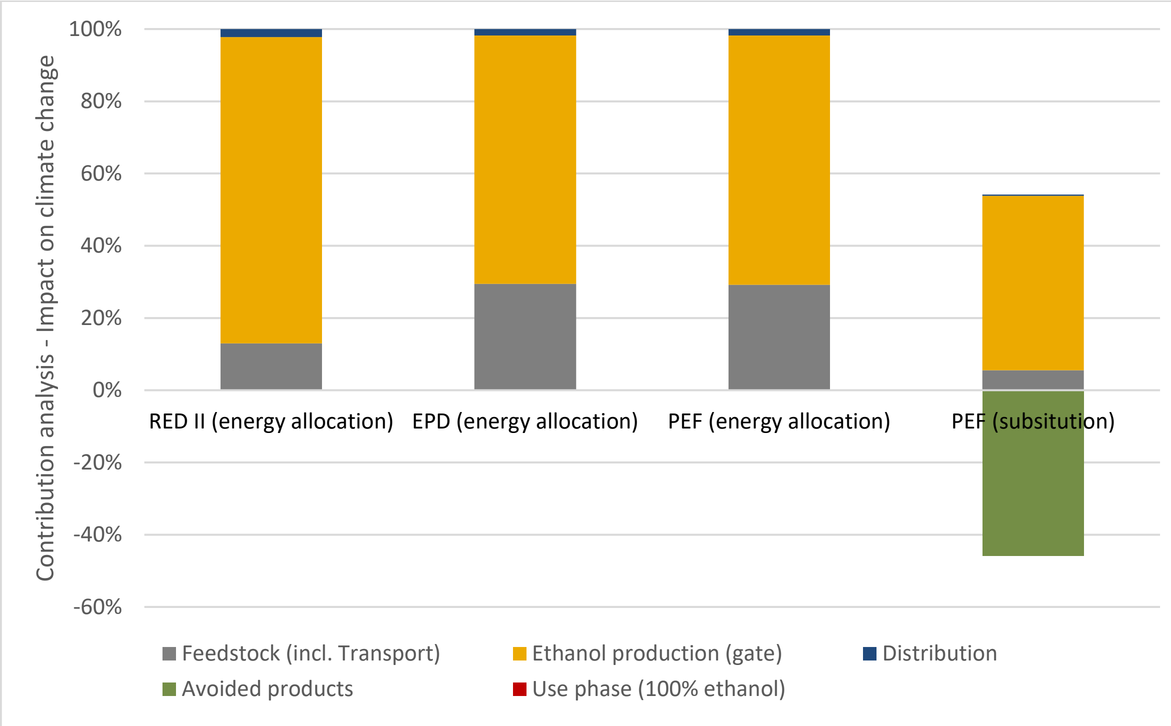

Figure 21. Analysis of the contribution to the impact of climate change of the different processes and life cycle stages of ethanol production and use as estimated based on the three frameworks; RED II, EPD and PEF.

10 PYROLYSIS OIL FROM USED TYRES

In this case study, the environmental impact of fuel from pyrolysis of used tyres is studied. Used tyres is a waste from passenger cars and trucks. Tyres contain both natural and synthetic rubber. In this case study, it is assumed that the biogenic carbon content in tyres is 48% and fossil carbon content is 52%, but this is highly depending on the recipe of the tyre and the type (passenger car, truck, summer or winter tyres) (Scandinavian Envirosystems, 2021). Tyres also contain, besides rubber, steel, synthetic fabric, carbon black, silica, sulphur, and other additives (Skenhall et al. 2012).

The main inputs to the pyrolysis process are tyre cuts, electricity, heat, water, and a chemical to reduce emissions of sulphur oxides. The main products are carbon black, pyrolysis oil, steel scrap and pyrolysis gas. The gas is used internally for heat purposes in this case study and therefore not included as a product exiting the system boundaries. The process thereby emits carbon dioxide from combustion of the pyrolysis gas and generates small amounts of waste for incineration (Olofsson & Tellblom, 2021).

10.1 SYSTEM BOUNDARIES

The main activities included in the system boundaries are transport of the waste tyres to a tyre recycling facility, cutting of tyres to tyre chips, transport to the pyrolysis plant in Uddevalla, pyrolysis, transport of the recycled oil to a refinery where it is upgraded and finally distribution and use of the fuel. No impact from tyre production and tyre use is included in the case study.

In the system boundaries of the PEF system, the pyrolysis oil is partly burdened with production of diesel according to an interpretation of the CFF. This is discussed further in chapter 10.2.2.

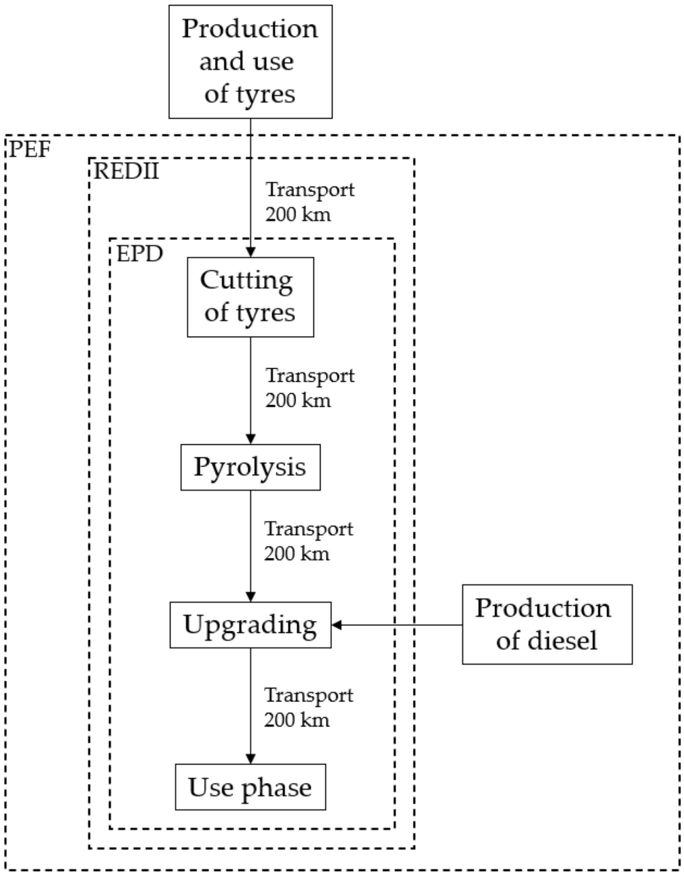

Figure 22. System boundaries in relation to the methods applied; RED II, EPD and PEF.

10.2 KEY INPUT DATA AND ASSUMPTIONS

The material and energy balance for the studied process were obtained from Scandinavian Envirosystems AB who is an industrial partner of the project. Data is based on a future plant planned in Uddevalla, Sweden. The data provided are, however, confidential and will not be displayed in detail in this report. The main feedstock is however used tyres. The pyrolysis fuel needs to be upgraded to remove possible impurities and to match fuel quality before use. The lower heating value of the pyrolysis oil before upgrading is approximately 40.5 MJ per kg.

No specific data has been obtained for the transport, refining and distribution for pyrolysis fuel. The main reason for this is this is a prospective case study and based on a theoretical supply chain for pyrolysis oil used as a fuel. Therefore, assumptions have been made by the LCA practitioner to avoid data gaps. All transport distances have been estimated to 200 km, as illustrated in the flow scheme above (Figure 22). Data on upgrading of the pyrolysis oil to fuel quality have been approximated with data on HVO production in Jogner & Nojpanya (2021).

Modelling of the pyrolysis process have been performed in the LCA software GaBi (Sphera, 2021).

It is assumed that both the pyrolysis gas and pyrolysis oil contain 48% biogenic carbon and it is only the fossil carbon dioxide emissions that contributes to climate change. This assumption is the same for all frameworks.

The electricity mix is modelled differently in the frameworks. In RED II, an average Swedish grid mix is used while in EPD and PEF a Nordic residual grid mix is used. Since the pyrolysis process is relatively electricity intensive, a renewable electricity source is tested in a sensitivity analysis for the EPD and PEF scenarios.

10.2.1 Multifunctional processes

Two multifunctional processes are included in the studied system: the pyrolysis process and the upgrading process. Three products are produced from used tyres in the pyrolysis process – pyrolysis oil, carbon black and steel scrap. Approximately 45% of the feedstock will be produced as pyrolysis oil, 30% as carbon black, 15% as steel and 10% as pyrolysis gas /Scandinavian Envirosystems, 2021).

Since the pyrolysis gas is used internally, no allocation has been performed for this product. In the upgrading process two products are produced: fuel and steam.

In the RED II framework, energy allocation is performed according to the directives. For the EPD and PEF framework, mass-based allocation is performed. Since the steel scrap fraction and the carbon black are products which will not be used as energy carriers in the next life cycle, mass-based allocation was assumed to reflect the material relationship better than if allocation were performed based on the materials' lower heating value.

10.2.2 Rules for material recycling, reuse, and energy recovery

According to the EPD and RED II frameworks, wastes carry no upstream burden from previous life cycles. Since used tyres is a waste, no impact from production of tyres is included within the system boundaries. Instead, the system boundaries start with collection (RED II) or cutting of tyres (EPD).

In the PEF framework, since waste is used as feedstock to produce pyrolysis oil, the CFF is applied. The use of CFF involves the emissions from primary materials (Ev). In this study, the primary material for upgraded pyrolysis fuel is interpreted as diesel rather than tyres. This leads to a production of diesel being included in the system boundary for PEF as well. In the equation below, the resulting CFF for the pyrolysis case is presented.

$$\boldsymbol{E = 0.5 * E_{REC} + 0.5 * E_V}$$

10.3 RESULTS AND DISCUSSION

The results of the climate change impact of the pyrolysis case study using the different frameworks are presented in Figure 23 below.

According to the results below, the different frameworks result in quite similar climate footprints of the pyrolysis fuel ranging from 45 to 56 g CO_2 eq./MJ fuel depending on the applied method. The EPD framework results in the highest climate change impact while the RED II framework results in the lowest. A major difference between these two scenarios is how the electricity production is modelled: the RED II framework only allows for an average national grid mix, while the EPD (and

PEF) framework allows for either a residual grid mix or electricity with a guarantee of origin certificate. Since the pyrolysis plant is not actually in place today and thus no guarantee of origin certificate exists, a Nordic residual grid mix was modelled. This also affects the footprint of the tyre shredding, which is mainly done with electricity

The main contributor to all frameworks is the fossil carbon dioxide emissions during the use phase, i.e., the combustion of fuel in a vehicle (see Figure 23). Depending on the type of tyres used as feedstock, the ratio of biogenic and fossil carbon may vary.

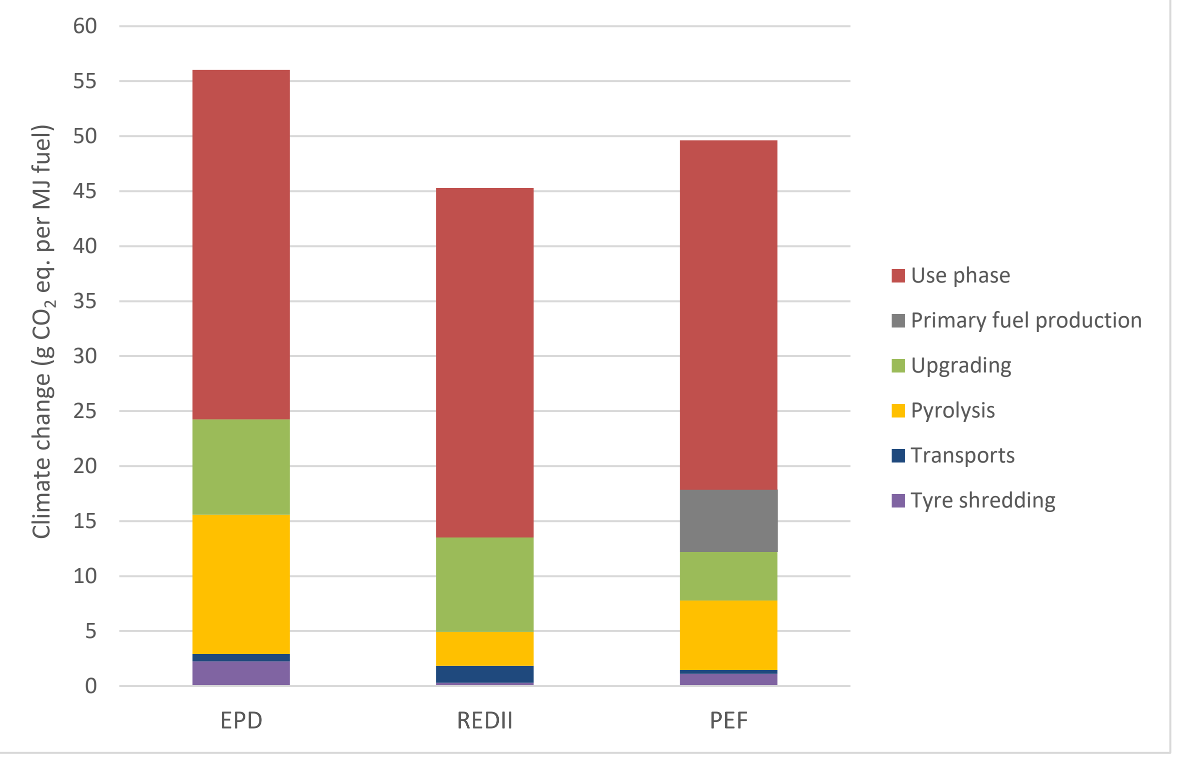

Figure 23. Results illustrating the impact on climate change from pyrolysis fuel according to the three frameworks RED II, EPD and PEF.

To test the influence of the choice of electricity production, a sensitivity analysis was performed where a renewable energy source was modelled in the EPD and PEF case. The result is presented in Figure 24 below. The RED II framework does not allow for using any other electricity mix than a national average grid mix.

The results show that if a renewable electricity source is used in the pyrolysis process the climate impact would be as good as equal for all the frameworks.

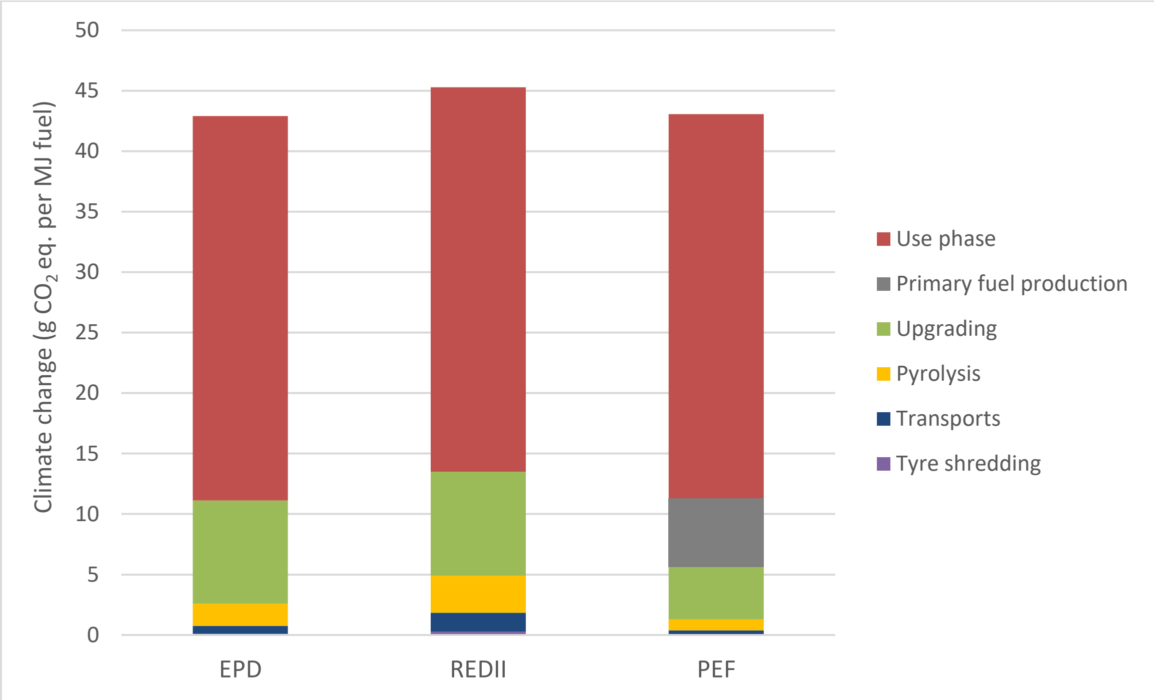

Figure 24. Results illustrating the impact on climate change from pyrolysis fuel using the three frameworks RED II, EPD and PEF, when the electricity mix is modelled as 100% hydropower in the EPD and PEF case.

11 META-ANALYSIS OF RESULTS

The concept of meta-analysis is well established in, e.g., medicine, where results from different studies are compiled with statistical methods to produce more certain results than what can be obtained from the individual studies (Borenstein *et al.* 2019).

However, we use the concept meta-analysis in a wider sense, based on the original meaning of the Greek word meta ("after" or "beyond"), to imply any analysis of a collection of completed LCAs. The aim of such an analysis can be to better understand the studies, to explain the difference in LCA results by identifying the key differences in methods, and, possibly to describe the meaning and validity of the different LCA results and formulate recommendations based on these findings. Several studies of this kind have been conducted before (Ekvall 1998, Ekvall 2006, Ekvall *et al.* 2020, Sandin *et al*. 2020, Miliutenko *et al*. 2020).

The objectives of this meta-analysis are to identify differences in results and conclusions from the application of RED II, EPD and PEF frameworks, and to explain the main reasons why the different frameworks lead to diverging results.

11.1 MODELING WASTE MANAGEMENT

The RED II, EPD and PEF frameworks diverge in the methods applied for modelling waste management. This can be very important for the assessment results when the biofuel is produced from waste. Our results indicate a much higher impact on climate for HVO and biogas when assessed with the PEF framework compared to the other frameworks (see Chapters 3-4 and Figure 25). The results are also sensitive to the interpretations and application of the Circular Footprint Formula (CFF), which defines how material production and waste management should be modelled in a PEF. In this section, we refer to the Product Environmental Footprint Category Rules Guidance, Version 6.3 (European Commission 2018b). The same information is available in the slightly more recent suggestions for updating the PEF framework (Zampori & Pant, 2019).

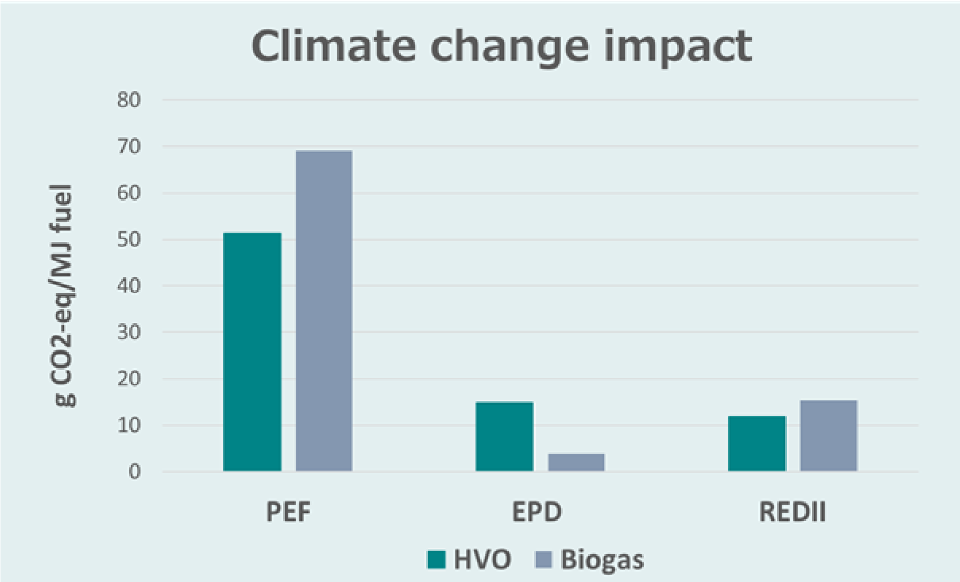

Figure 25. Preliminary results from the assessment of HVO produced from used cooking oil and of biogas produced through digestion of food waste (Poulikidou et al. 2021).

11.1.1 Substituting biogas in the PEF framework

The PEF guide considers biogas from anaerobic digestion a form of energy recovery (European Commission 2018b, p. 125). The CFF gives a credit for environmental burdens avoided when the recovered energy substitutes another energy source (ibid. pp. 112-114). To avoid double-counting of the environmental benefits of energy recovery, the recovered energy should be modelled as the primary energy substituted by the biogas (ibid. p. 114). We assumed that the biogas substitutes fossil natural gas, and that the food products from which biogas are produced will be credited for the reduced production and use of this natural gas. To avoid double counting, we modelled the production and use of biogas as production and use of natural gas. In other words: the biogas was assigned the same climate impact as natural gas. This is the reason why the preliminary PEF results for the biogas are much higher than the EPD and RED II results.

When modelling material recycling, a PEF does not account for any benefits or burdens in the use phase induced by substituting virgin material by recycled material. The burdens of recycling and credits for avoided virgin production are accounted for up to the point of substitution only (European Commission 2018b, p. 122). For biogas the point of substitution is before the combustion in the vehicle: biogas substitutes fossil natural gas at the tank station. If the biogas is distributed in a gas grid, the substitution occurs when the biogas is fed into the grid.

If the point of substitution defines how recovery of biogas is modelled, the digested food will be credited with the avoided production of natural gas, but not with the reduced use of fossil gas in vehicles. To avoid doble counting, the biogas life cycle should then be modelled as the production of fossil natural gas and the use of biogas. The climate impact indicated in the PEF results would be greatly reduced, because most of the climate impact of natural gas is from its combustion. In fact, with this interpretation of the CFF, the PEF results for biogas would be in the same order as the RED II results (Figure 6 and Figure 26). Whether PEF or RED II would indicate a higher climate impact depends on whether the production of biogas or natural gas has the higher climate impact. This, in turn, depends on where the leakage of methane is the highest.

Two different interpretations of the CFF seem possible here: to model the production and use of biogas as natural gas, or to model the biogas as the production of natural gas but the use of biogas. These interpretations will generate very different PEF results. As long as the PEF guide is not clear on this point, fuel producers can model biogas as the production of natural gas and the use of biogas. Food producers, on the other hand, can give their product a credit for avoided production and use of natural gas. This means the PEF results for food and biogas will not be additive: the food will get a credit for avoided use of natural gas, but the biogas will not carry the burdens of natural-gas use. In this sense, the environmental benefits of energy recovery will be double counted.

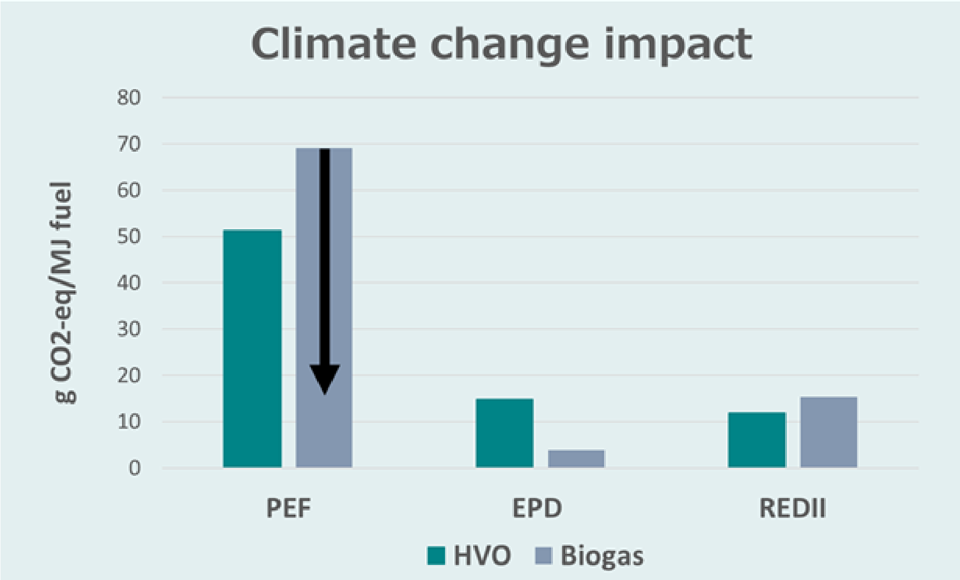

Figure 26. PEF results on biogas are greatly reduced if the impacts of substituting natural gas are only accounted for up to the point of substitution.

11.1.2 Virgin material production in HVO

We modelled HVO production from used cooking oil (UCO) as material recycling (see Chapter 3). The PEF framework is different from EPD and RED II in that a PEF, through the CFF, assigns a share of the burdens of virgin material production to the use of recycled material (see Section 2.3 and European Commission 2018b, pp. 112-114). The size of this share depends on a material-specific allocation factor A, and on quality losses in the recycled material compared to the virgin material. The quality is typically measured using the price of the materials (ibid. pp. 116-117). This is the main reason why PEF results indicate a much higher climate impact for HVO, compared to the EPD and RED II frameworks. Our preliminary PEF calculations included half the impacts of the production of cooking oil, because A=0.5 as default when no other value is available (ibid. p. 114), and because we found that HVO is probably not cheaper than the cooking oil (Jogner & Nojpanya 2021, cf. Figure 27).

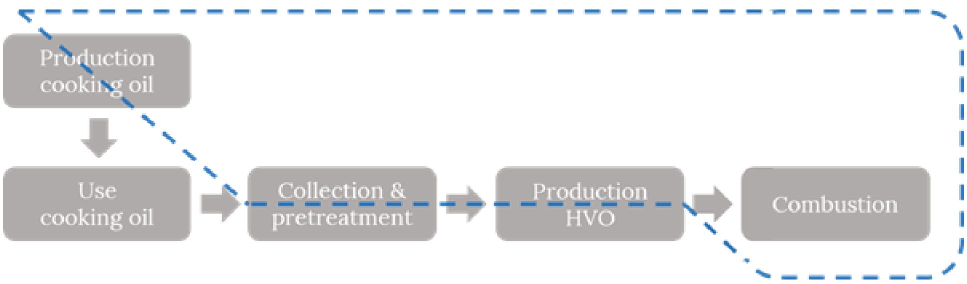

Figure 27. The preliminary PEF calculations on HVO included half the impacts of the production of cooking oil and half the impacts of the recycling into HVO.

After a more careful interpretation of the PEF guide, assisted by the PEF Helpdesk and instruction videos, we found that the virgin-material production included in the assessment should not be the production of the cooking oil, but the production of the substituted virgin material, i.e., the material that would have been used if the UCO was not available. In parallel to the modelling of energy recovery discussed above, this aims to avoid double counting: the cooking oil gets a credit for substituting another material after recycling, and the impacts of the substituted material use are instead assigned to the user of the recycled material. The credit and burdens are both affected by the difference in quality at the point of substitution (European Commission 2018b, p. 113).

The misinterpretation that the system should include the production of the cooking oil is easily made because the burdens of the virgin material assigned to the use of recycled material are in the CFF denoted E_V, while the burdens of virgin material substituted at recycling are denoted E^*_V (European Commission 2018b, pp. 112-114). A change in the notation would reduce the risk of misinterpretation.

With the correct interpretation of the CFF, we still have to identify what virgin material is substituted. This depends on where in the production chain the substitution is made. Pre-treated UCO can replace virgin vegetable oils as input to the HVO production of the same kind as in the cooking oil (Figure 28). This means that the environmental impacts of virgin production can be similar, compared to the impacts of cooking-oil production. The PEF calculations will include half the impacts of producing the vegetable oils, unless the price of pre-treated UCO is less than the price of the vegetable oils it substitutes. Our price data suggest a significant increase in prices between 2019 and 2021. However, the price and its increase are about the same for rapeseed oil, palm oil and UCO. It is reasonable to assume that the value and price of pre-treated UCO vary with the price of the virgin vegetable oil it substitutes. This means the PEF of the HVO will include about half the impacts of producing the vegetable oils, and the PEF results in Section 3 are approximately the same as our preliminary results (cf. Figure 4 and Figure 25).

Note that these results are sensitive to the price ratio between the recycled and virgin materials. In our case study on ethanol from bread residues, the substituted virgin production is wheat and the price ratio of bread residues to wheat is 0.56 (see Section 8.2). This means the PEF calculations include only 28% of the burdens of wheat production ($A^*Q_{Sin}/Q_P = 0.5^*0.56 = 0.28$).

If the price of the recycled material (bread residues, pre-treated UCO, etc.) becomes very low, the PEF calculations will include a small share of the primary production only. The PEF results might then even be lower than the EPD and RED II results. This is because the PEF calculations include only half the climate impact of recycling, while EPD and RED II includes the full impact of recycling.

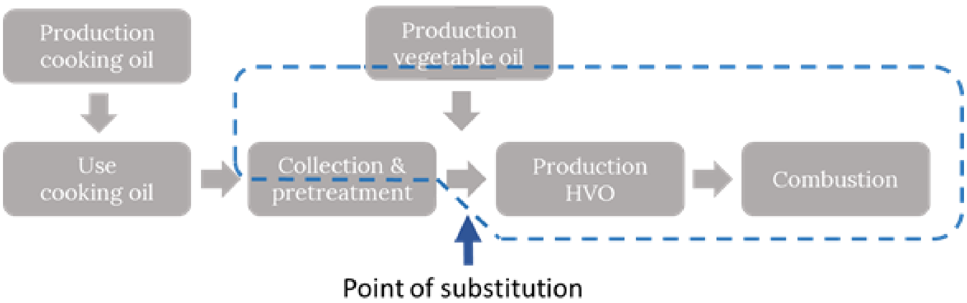

Figure 28. If pre-treated UCO substitutes vegetable oils, PEF is likely to assign half of the virgin oil production to the UCO-based HVO. However, if the price of pre-treated UCO is low, PEF might assign only a small share of the virgin production to the HVO.

However, HVO produced from UCO can also substitute HVO produced from vegetable oil. The point of substitution is then after the HVO production (see **Fel! Hittar inte referenskälla.**). The HVO produced from UCO is assigned half the production of the substituted HVO, if the two fuels have similar quality and price. In this case, the PEF can yield results that are similar to our preliminary calculations. This is because both calculations include 50% of the impacts of virgin oil production, 50% of the impacts of collection and pre-treatment of UCO, and a HVO production process or 50% of two HVO production processes.

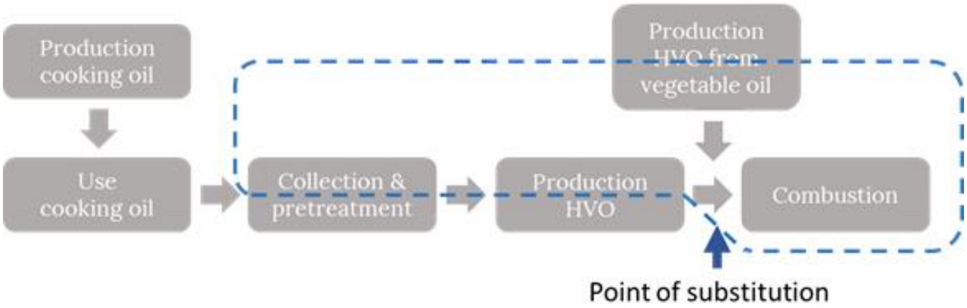

Figure 29. If UCO-based HVO substitutes other HVO produced from vegetable oils, PEF is likely to assign half of the virgin HVO production to the UCO-based HVO.

The intention to produce HVO from UCO is to substitute fossil diesel in the transport sector. Using this as basis for the assessment means the cooking oil is credited with a share of the impacts avoided when the production of the diesel is displaced (Figure 30). This share will be 50%, unless the HVO is cheaper than diesel. Note that the HVO calculations will still include the combustion of HVO and not the impacts of diesel combustion. This is because the CFF only accounts for impacts of recycling and virgin material production up to the point of substitution (European Commission 2018b, p. 122).

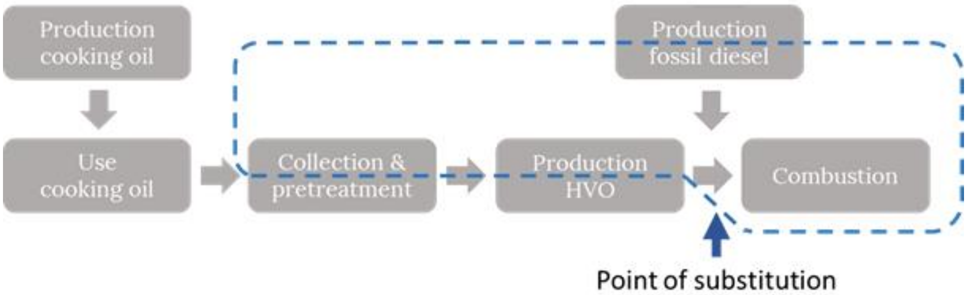

Figure 30. If HVO substitutes diesel in the PEF model, the PEF results for the HVO are likely to include half the impacts of the diesel production.

Finally, in a broader systems context, transportation based on HVO might substitute transportation based on fossil fuel. The cost and quality of transportation is not likely to be noticeably lower when HVO is used as fuel in the vehicle. This means the PEF model of the HVO will include half the impacts of producing and using the fossil fuel. This would greatly increase the climate impact indicated by the PEF.

The point of substitution can clearly be important for the PEF results for HVO, just like it is for the biogas (see above). However, the point of substitution is even harder to identify for the UCO-based

HVO, since more options are on the table. The PEF guide does not give sufficient guidance on this point. We even got conflicting advice from the PEF Helpdesk. Further guidance could perhaps be included in PEF Category Rules for biofuels. Until then, the choice of point of substitution appears to remain subjective and the PEF results for UCO-based HVO will depend on this subjective methodological decision (Figure 31).

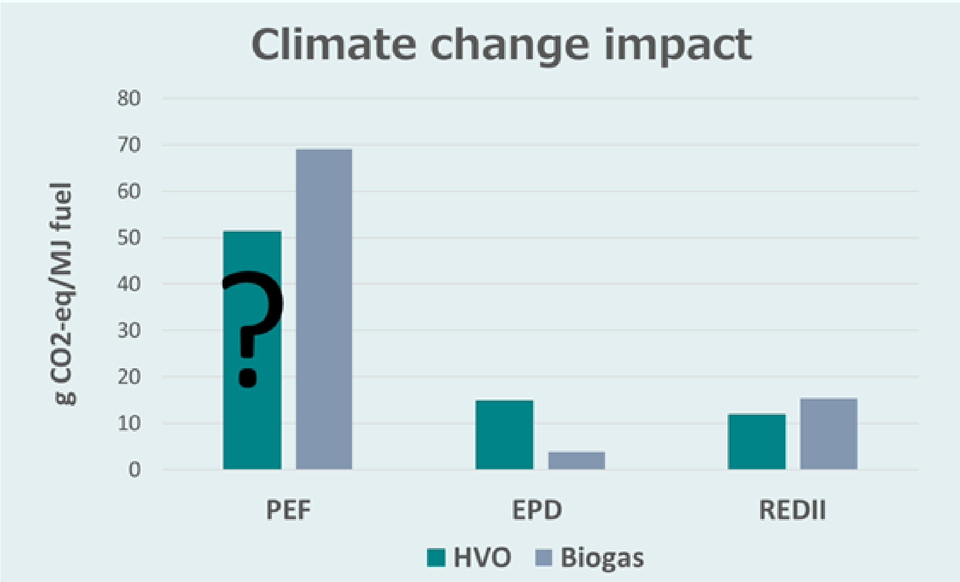

Figure 31. PEF results for the HVO depend strongly on the subjective choice of the point of substitution.

11.1.3 Digestion in EPD

Next after the high climate impact indicated by the PEF calculations, the biggest difference in results in Figure 25 is between EPD and RED II results on biogas. The main reason for this is a difference in system boundaries at the anaerobic digestion where the biogas is produced (see Figure 5 and Figure 32). RED II stipulates that emissions from digestion shall be included in the climate assessment of biogas (European Commission 2018a), and these emissions dominate the RED II results (Figure 7). Our EPD results do not include these emissions and, hence, indicate a much lower climate impact for biogas.

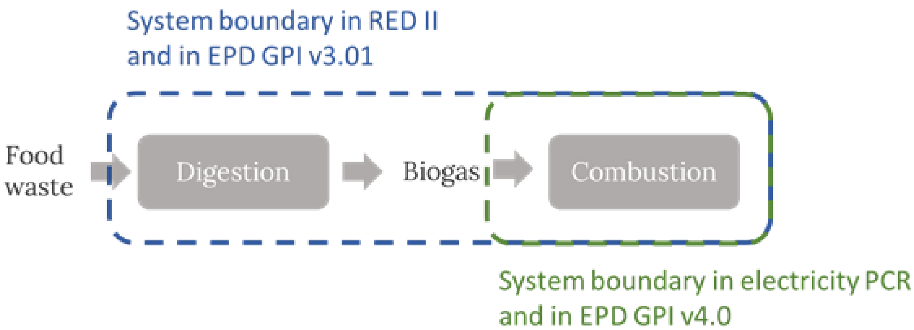

Figure 32. RED II calculations for biogas includes emissions from the digestion plant. In the EPD framework, the stipulated system boundary varies between documents.

The EPD framework includes no product category rules (PCR) for biogas or biofuels in general. We instead refer to the PCR for electricity, steam, and hot water. This document states that when electricity is produced from biogas, the biogas shall not carry any burdens from the digestion. These burdens shall instead be allocated to the product that generates the digested waste (EPD International 2007, p. 13).

However, this rule appears to contradict version 3.01 of the EPD General Programme Instructions (GPI), which state that the product that generates the waste shall carry burdens only to the point where the waste enters the gates of the waste treatment facility (EPD International 2019, p. 62). This implies that the digestion plant is part of the biogas life cycle. With this shift in the system boundary, the climate impact of biogas will be roughly the same in the EPD and RED II frameworks (see Figure 33).

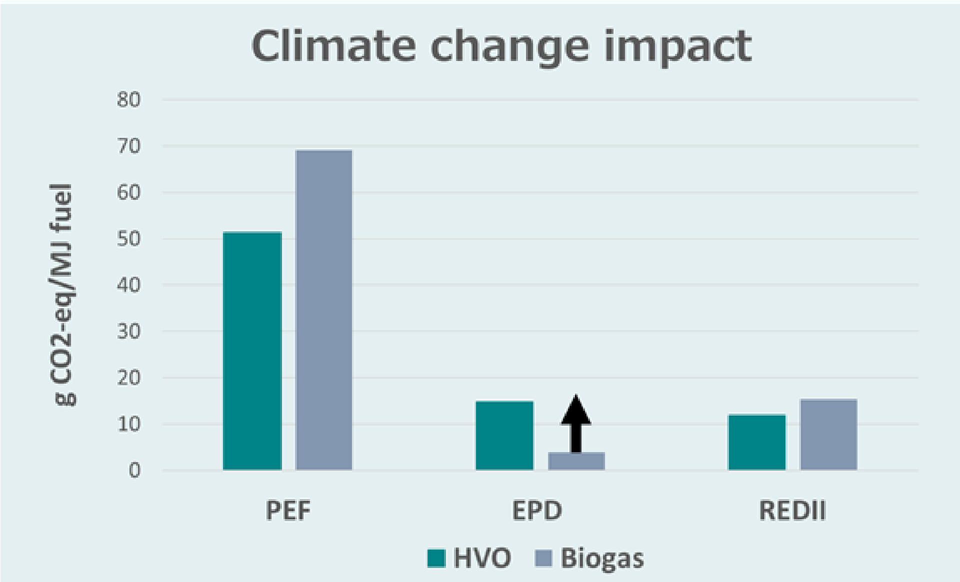

Figure 33. EPD results for the biogas will be similar to the RED II results, if the emissions from the digestion plant are included in the calculation.

On the other hand, the most recent version of the EPD GPI state that the impacts of waste processing shall be assigned to the product that generates the waste until the end-of-waste state is reached (EPD International 2021, p. 66). Emissions from waste incineration with energy recovery are assigned to the product that generates the waste unless the waste has a positive economic value (ibid. p. 67). In parallel, it is reasonable to allocate the climate impact of the digestion process to the products that generate the waste. Based on this document, our EPD calculations appear to be accurate.

The rules for modelling waste management in EPD varies between documents and over time. This has a large impact on the EPD results for biogas. EPD results for biogas and other biofuels could be made more robust through the development of a PCR for biofuel.

11.2 ALLOCATION OF MULTIFUNCTION PROCESSES

The RED II, EPD and PEF frameworks diverge in the approach to modelling co-products. This can be important for the total result when the biofuel has important co-products, which is the case in several cases. For example, ethanol produced from corn and bread residues both generate by-products that can serve as animal feed: dried distillers' grains with solubles (DDGS) and drank, respectively (see Chapters 7-8). Ethanol produced from saw dust generates several by-products: lignin, furfural, turpentine, and biogas (Chapter 9). Pyrolysis of used tires also generates a range of co-products besides the pyrolysis oil: carbon black, steel scrap, and pyrolysis gas (Chapter 10).

The most important difference in allocation methods is that the PEF framework allows for system expansion with substitution, which is prohibited in the two other frameworks. Substitution can greatly reduce the PEF results, as evident from Figure 17 and Figure 20. However, PEF allows for a free choice between allocation and substitution. This means that PEF calculations do not necessarily diverge from EPD and RED II calculations on this point.

When multifunction processes are modelled with substitution in a PEF, the results are highly sensitive to what is substituted and how far the system is expanded. This is clear from our case studies on ethanol production from bread residues and corn. In both cases, the by-product (drank and DDGS) is assumed to replace soybean meal as animal feed, and the system is expanded to include that avoided burdens of substituted soybean production. This expansion greatly reduces the PEF results. Figure 17 indicates that substitution reduces the PEF result by 85%, compared to partitioning the climate impact of ethanol production between ethanol and drank in proportion to their energy content. With substitution, PEF indicates a lower climate impact than RED II and EPD even though the PEF calculations include part of the impacts of primary wheat.

In our case study on ethanol from corn, however, the system is expanded further to account for the fact that reduced soybean production leads to reduced production of soybean oil. This is in our model compensated by an increase in palm oil production, which affects the climate much more than soybean cultivation. The system expansion with reduced soybean production and increase palm oil production is the main reason why PEF indicates a greater climate impact than RED II and EPD in Figure 15.

The free choice between allocation and substitution makes it difficult to compare results from different PEFs of biofuel. The important and often uncertain assumptions on what is substituted adds to this problem. However, PEF calculations could be made more reproducible through the development of PEFCR for biofuel that stipulates how the most common or important multifunctional processes should be modelled.

Even if the EPD framework prohibits substitution, it allows for a broad range of allocation approaches. This can contribute to making comparisons difficult between different EPDs of biofuel. The EPD calculations can also be made more reproducible through the development of a PCR for biofuel.

The RED II methodology is more well-defined than PEF and EPD, because it stipulates what method should be used: allocation should be based on the energy content of products, except for the co-production of electricity and heat where allocation should be based on the exergy.

11.3 MODELING ELECTRICITY SUPPLY

The RED II, EPD and PEF frameworks diverge slightly in how electricity production is modelled. RED II stipulates that electricity bought from the grid should be modelled to reflect the average emissions from “the production and distribution of electricity in a defined region” (European Commission 2018a, p. 154).

Version 3.01 of the General Programme Instructions (GPI) of EPD International stipulates that electricity production should be modelled using data for a supplier and technology if the origin can be guaranteed (EPD International 2019, pp. 57-58). In other cases, data reflecting the residual mix in the country or market should be used, if possible. When data on the residual mix cannot be found, data reflecting the total production mix in the country or market should be used. The recent Version 4.0 of the GPI, stipulates the use of residual or consumption mix on the markets, and does not allow for the use of data reflecting the national or production mix (EPD International 2021, pp. 64-65).

In a PEF, the electricity production should be modelled using data for a technology or a supplier if a contract clearly assigns this production to the process that use the electricity. In other cases, data reflecting the national consumption mix should be used (European Commission 2018b, pp. 89-90). However, for electricity used in Sweden national data are replaced by data representing four Nordic countries: Sweden, Finland, Norway and Denmark (Granström *et al*. 2011; EI 2021; Spak 2021).

There is room for interpretations in the guidance on electricity modelling. When RED II is applied, for example, decisions have to be made on how to define the region and on whether to use data on the production or consumption mix in this region

The EPD GPI Version 3.01 leaves room for choosing between the national or market mix. Version 4.0 allows only for the use of the market mix, but leaves the question open how the market should be defined: is the market national or Nordic (i.e., integrating Sweden, Finland, Norway and Denmark), or does it include a wider range of European countries? This could be clarified in a PCR for biofuel. However, since the modelling of electricity supply is relevant for almost all product groups, it might be better to add a clarification in coming versions of the EPD GPI.

The impact on climate change of electricity production can vary significantly depending on what data are used. The choice of electricity data can be important for the total assessment results when other climate impacts in the system are very small – for example, in an EPD of biogas where the emissions from digestion are excluded from the calculations (see Figure 6 and Figure 8). It is, of course, also important in the few cases where the production and distribution of the fuel require large quantities of electricity. An example of this is the pyrolysis of used tires (cf. Figure 23and Figure 24). In most of our calculations, however, the climate impact of the fuel is often not seriously affected by the choice of electricity data, because the production of most biofuels requires little electricity.

Note that, if the region in RED II and the market in EPD are both defined to be Nordic, the three frameworks can give quite similar guidance on how to model the supply of electricity used in Sweden.

12 REFLECTIONS ON THE LCA FRAMEWORKS AND MASS BALANCE CERTIFICATION SYSTEMS

Both MBC schemes and LCA calculations of environmental impact are being used as a basis for communication of environmental “advantages” of certain products and value chains. In addition, both approaches are often used by the same companies. As a result, there may be confusion about the interpretation of the information that is communicated. The purpose of the reflections presented here is thus to reduce such confusion.

The chapter is divided into three sections:

1. Description of the diverting purposes, areas of use and system boundaries of MBC schemes and LCA analysis to clarify in what respect the scope of these systems differ and where they overlap.
2. Description of the principles for GHG calculation used in MBC schemes, compared to those of RED II.
3. A qualitative comparison for two of the cases studies presented above: HVO from used cooking oil (UCO); and pyrolysis oil from used tyres.

12.1 PURPOSE AND SYSTEM BOUNDARIES OF MBC SCHEMES VS LCA

MBC schemes, being one type of chain of custody certification schemes, and LCA relate, in generalized terms, to similar life cycle-oriented system boundaries. However, the *purpose* of applying these methods to the system differ and thus also the type of knowledge that you derive from the exercise. This is valid for all types of CoCC schemes, here, however, only the MBC schemes are discussed.

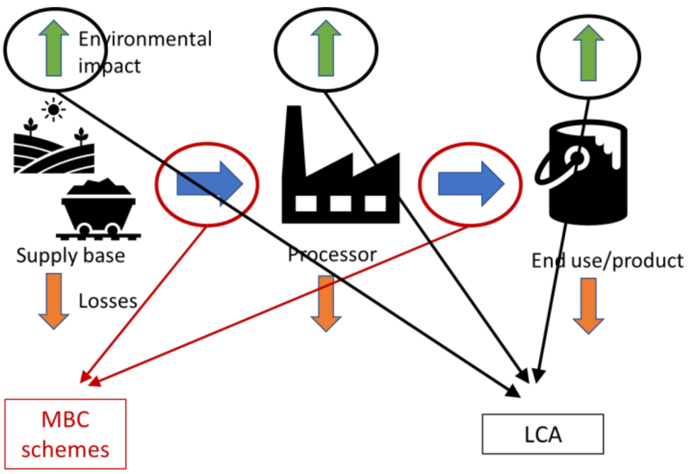

Figure 34. Illustration of the aspects in focus for MBC schemes vs LCA. The losses that are incurred in each step are vital for both methods.

The purpose of the MBC schemes is twofold. Firstly, it is to verify that the company’s information about the supply chain for the products that it sells and markets is correct. This includes where the products are produced, which material and other inputs that are used for this production and the *amount* of these inputs that are used. Consequently, the parts of the supply chain that are in focus for the MBC are the actual linkages between the different steps in the chain, together with the losses (to be able to determine the total amount of input).

Secondly, it is to verify the sustainability of this supply chain. This purpose is just as important as the primary one but completely reliant on that the primary purpose is fulfilled. Which aspects of sustainability that are included in different certifications vary between certification schemes and between what is included in company specific certifications. As an example, the ISCC PLUS (and the ISCC EU) scheme, include six sustainability principles: Protection of land with high biodiversity value or high carbon stock; Environmentally responsible production to protect soil, water, and air; Safe working conditions; Compliance with human, labour, and land rights; Compliance with laws and international treaties, and finally; Good management practices and continuous improvement. In addition, verification of GHG emissions can be made as a voluntary add-on (mandatory in ISCC EU). (ISCC PLUS, 2019)

The system boundary of MBC schemes includes the entire value chain from supply base to end use. The certification of a specific company controls the use of certified *input* into the company's own system (e.g., that they buy certified raw material), and control of their own process and losses of material, which then makes it possible for them to sell certified products to the next step in the chain. In this way, the entire chain is covered. However, since certification in general does not cover the end customer, the use and disposal phase (grave) may not be included.

The primary (and only) purpose of LCA is to quantify the environmental impact of a certain product over its life cycle. To do this, reliable data is needed on (amongst other things) the types of inputs that are used and the losses along the supply chain. Consequently, LCA analysis for a specific product from a specific company uses the same value chain data as is described in the company's book-keeping system and verified through the MBC scheme. More general LCA analyses of products are instead made under the assumption about a specific type of value chain, including use of raw material of a specific type and sourced from a specific country or area.

The system boundary of LCA depends on the more detailed purpose of the analysis and on the framework used but covers at a principal level the entire chain from cradle-to-grave. When dealing with processes with multiple inputs, multiple outputs or that involves recycling, reuse, or recovery of materials, the LCA frameworks deals with this through different allocation approaches, which partly correspond to the specific provisions of the MBC schemes.

Consequently, the application of MBC schemes and LCA are rather sequential, or depending on each other, than overlapping in their focus. The purpose of the MBC schemes (or other CoCC schemes) is to provide reliable data on types and total amounts of raw material use for the value chains connected to the production of specific products in a specific process (or processes) located at specific production sites. LCA is then used to quantify specific environmental impact (per product unit) from these value chains. Especially, when GHG emissions are included in the certification, LCA is required as a tool for quantifying these emissions. For comparing the approaches in more detail, it is thus the MBC provisions related to calculation of GHG emissions that are relevant.

12.2 GHG CALCULATION PRINCIPLES IN MBC SCHEMES

For the MBC schemes, calculation of GHG emissions is voluntary but can be included in the certification.[10] In general, the same provisions as for RED II then apply (see Section 2.1), but with some additional flexibility.

In REDCert[2], for instance, it says that the underlying calculation methodology must either follow the principles described in the REDcert EU scheme or meet the requirements of a valid life cycle assessment, for instance, according to ISO 14040. The RSB AP specifies that the assessment should follow the rules as specified in ISO 14044. (REDCert[2], 2019; RSB AP, 2018)

In ISCC PLUS, the calculation of GHG emissions should follow the same provisions as for ISCC EU, but with added flexibility with regard to:

- The sources of emissions factors, which means that also Ecoinvent or other relevant databases or literature can be used.
- Calculation methodologies, which next to the RED or ISCC, also can be based on ISO 14040/44 or ISO 14064/67.
- That aggregation of different incoming GHG values for all input materials of the same kind is possible (average values may be used).
- Allocation of emissions to main and co-products, which can be based on energy content, mass, or other types of allocation (the most suitable method should be used).
- That calculations can cover the whole life cycle (cradle-to-grave) or to the factory gate (cradle-to-gate), but this should be transparent. (ISCC EU, 2021; ISCC PLUS, 2019)

For the allocation of material use between products in processes where, for example, bio-based and fossil feedstocks are co-processed together there are guidelines set up. (ISCC, 2017) In the ISCC system, these guidelines are the same, regardless of whether the products consist of fuels or other products, and include that:

- The quantity of co-processed biofuel should be determined according to the energy balance and efficiency of the co-processing process.
- Specific bio-yields that take into account the difference of bio and fossil inputs and processes should be used, when determining this quantity.

Thus, in a simultaneous co-processing of bio and fossil inputs, the amount of co-processed biofuels should be calculated based on the site-specific and process specific bio-yield of the process. It can be calculated based on energetic determination or through the efficiency/losses of a process (e.g., via an experimental set-up) or via 12C or 14C analyses. If different approaches are used and result in different results, the conservative approach should be followed. (ISCC, 2017).

[10] Other regions and countries in the world have regulations on the sustainability of biofuels as well. The detailed provisions of those systems are out of scope of this project.

The corresponding provisions for REDCert[2] allow for larger flexibility, in that all different types of bio-based material are aggregated together, and that the calculation may be based on equivalent yields for fossil material.

12.3 QUALITATIVE COMPARISON OF GHG EMISSION CALCULATIONS

In this section, two of the case studies above are qualitatively compared with the provisions of the MBC schemes. It should be noted that the production of biofuels that are used in the EU cannot be certified according to these schemes, while the comparison is made only for the purpose of illustrating differences and similarities.

The comparison is made for the cases studies: HVO from used cooking oil (UCO); and pyrolysis oil from used tyres. Further, the comparison focuses entirely on the differences between GHG calculations based on RED II, and calculations allowed under MBC schemes. The comparison is made on a qualitative level, only discussing the principles used for the calculations. This means that no specific assumptions about volumes of raw material or end products are made.

12.4 PRODUCTION OF HVO FROM UCO

As discussed above, MBC schemes are used to verify processes where different types of raw materials are mixed and more than one final product is produced. Therefore, interesting differences arise especially for that type of process. Below, a case study variant has therefore been added, in addition to the original HVO from UCO case study.

As a background, it can be noted that HVO is produced in both stand-alone HVO production plants, that only use bio-based raw material, and plants in which the bio-based HVO production is integrated with fossil production.

Most production of HVO takes place in stand-alone HVO plants, even if a multitude of different bio-based raw material streams (both waste streams and virgin fatty raw material) are mostly used. In many cases, the production is also a mix of different HVO products, including some shares of gasoline and jet fuels, apart from diesel fuel.

One example of an integrated process is the HVO production of Preem, in which bio-based and fossil raw materials are co-processed in some of the refinery steps. In the so called Green Hydro Treater (GHT), the hydrogenation, hydrogenolysis and the isomerization processes are integrated. For processing optimization reasons, the input consists of 50% bio-based raw material (pre-treated bio-based oils) and 50% fossil light gas oil. The entire production from the GHT consists of different diesel fuels, some H_2, naphtha and gaseous carbon hydrates (Preemraff, 2017).

12.4.1 Case study HVO from UCO

The system boundaries used in the case study of HVO production from UCO are described in Figure 3. In this case, it is assumed that equal amounts of UCO from palm and rape oil of the same quality are used to produce HVO in a stand-alone HVO production site. This results in that the share of palm and rape oil derived HVO is the same as the raw material shares (50/50).

In this case, the calculation of specific GHG emissions would normally not be affected at all from being based on the provisions in the MBC schemes instead of those in RED II, since there is no mixing of different raw materials within the system boundary.

However, MBC schemes offer greater flexibility with regard to the methodology and data sources to choose. Consequently, depending on which framework that is chosen by the certified company, the result could instead coincide with the ones from the EPD or PEF frameworks, given that these frameworks are estimated to follow the requirements of a valid life cycle assessment and that the methodology chosen is transparently described. The MBC schemes provides data on "actual" material flows to use as a basis for the LCA calculations, but do not stipulate anything about the methods used for co-product allocation in the calculation of specific emissions.

According to an MBC scheme, the producer would also have the freedom to allocate between co-products on other basis than energy (if suitable). This would, however, only make a difference if allocation between co-products is actually made, which is not the case in this case study. Further, the MBC schemes allow averaging of incoming GHG data for the same product, given that it is based on the same type of raw material (i.e., bio-based, recycled or fossil based). The aggregation of UCO from different sources, such as from China and Sweden, may thus be aggregated together and an average presented. This is not allowed under RED II.

If some share of the raw material consists of a raw material that differs in quality from the UCO and is not classified as waste or residues, such as for instance virgin rape seed oil, instead of UCO, the situation would change in two ways:

1) The system boundary for RED II would change, in accordance with the RED II methodology for calculating GHG savings (see Section 2.1). For HVO based on virgin oil, emissions would then include (a share of) the entire value chain from cultivation of the rape seed, which means that the difference between GHG data for different streams would be larger.
2) The quality of the raw material for the HVO production process cannot be seen as equal anymore. This means that the yield from the process may be impacted by the change in composition.

The potentially different yields for the two raw materials are treated differently between RED II and between different MBC schemes:

- According to RED II, GHG emissions should be calculated for each raw material specifically.
- IPCC PLUS regulates that site-specific yields for each raw material should be used. Therefore, the shares in the final product may differ slightly, also for equal input into the HVO production.
- REDcert[2] allows aggregation of all bio-based material, which means partly that no distinction is made between the origin or type of the raw material as long as it is bio-based, and, partly, that average GHG emissions are reported. In addition, the calculation may be based on equivalent yields for fossil material. The RSB AP scheme has a similar approach, based on normalisation of the different feedstocks based on their "chemical value".

12.4.2 Case study variant: HVO diesel and gasoline from UCO and virgin oil

In the case study variant, we assume partly that half of the raw material consists of virgin oil, instead of UCO (as discussed above), partly that the HVO production process produces both HVO diesel (80%) and renewable gasoline (20%), while the value chain in all other respects is the same (see Figure 35). A case in which half of the raw material consisted of fossil oil would be even more relevant to the MBC schemes, but in that case the RED II do not include any requirements or guidelines on how to calculate GHG emissions.

In this case, an additional aspect is that the markets for HVO diesel and renewable gasoline may differ. This variant is therefore used to illustrate specifically the market effects, that may arise as a result of varying taxes and regulation, supply and demand or public opinion (linked to different raw materials in different countries or markets). Differences on the market side will of course impact the interest of the producer to deliver different products. This change may incur more dramatic differences between the RED II framework and MBC schemes.

When following the RED II regulation, all HVO derived from virgin oil would be equally split between diesel and gasoline, as would the UCO derived fuel. If all yields were the same for both raw materials it would thus be 40/40 diesel and 10/10 gasoline. The GHG data per MJ of fuel would differ considerably depending on raw material, due to the differences in system boundary, and be reported separately.

If the production was instead certified in accordance with MBC schemes, the calculation of specific GHG data for each product and raw material would be similar as for RED II but depend on the certification scheme used and the choices made by the producer, as described above.

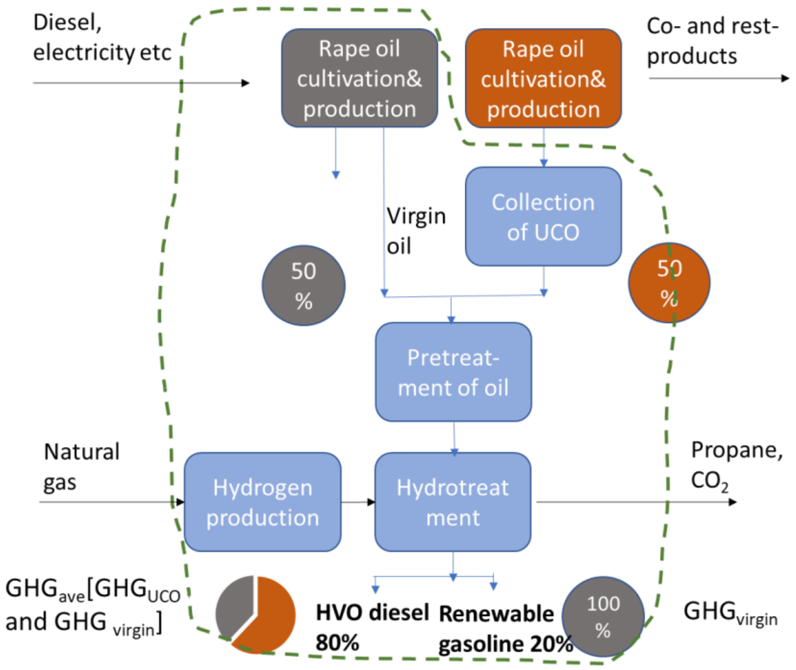

Figure 35. Simplified flow chart variant II of the case study, in which both HVO diesel and gasoline is produced in the HVO production process. Here, the assumption of two different markets for different (bio-based) products is illustrated. The circles at the bottom of the figure indicates that the shares of raw materials may, according to MBC schemes, be attributed freely between the final products. (The actual shares, as well as the choice of variants of specifically rape oil, are just an example.)

A major difference is, however, that the total production could be freely attributed between the products. This means that if the market for HVO diesel from virgin oil is relatively less advantageous, all UCO-derived fuel could be attributed to the diesel market (as long as total UCO-derived production is less or equal to the produced amount of diesel). In consequence, 100 % of the renewable gasoline produced would then be attributed to the production based on virgin oil. Reported GHG data would then follow this attribution, so that for gasoline, the GHG data would be based on data for virgin oil and GHG data for the diesel would be the weighted average of the GHG data based on UCO and virgin oil, respectively (see Figure 35).

This type of free attribution is allowed for all MBC schemes mentioned above. However, this does not mean that all MBC certified producers utilize this (or other) possibility. Note also that fuel producers that deliver biofuels for use in the EU are required to follow the RED II requirements, and thus cannot apply free attribution in this way.

12.5 PYROLYSIS OIL FROM USED TYRES

In the case of pyrolysis oil production from used tyres, the raw material used consists of a mixture of fossil and bio-based rubber and the process results in several co-products (pyrolysis oil, which is upgraded to fuel; carbon black; and steel scrap). This means that this case represents directly the type of process whose products could be certified through an MBC scheme (if not sold as biofuel in the EU).

According to RED II regulations, only the amount of fuel oil that can be produced from the bio-based raw material (i.e., 48% of all used tyre material processed) can be classified as (advanced) biofuel. However, it should be noted, that there are limited mass balance features included also in the RED regulation. According to these, it would be possible to sell 48% of the production as (pure) biofuel, and 52% as (fossil) waste-based fuel instead of all fuel as a mixture. In addition, if the shares vary over time, the production and marketed amounts can be balanced over time. This means that also according to the RED II, the biogenic content of the marketed fuel does not need to be physically verifiable.

If applying an MBC scheme, the increased flexibility with regard to the methodology and data sources used for GHG calculations, for allocation between co-products on other basis than energy (if suitable), and in relation to the uses of specific yields would be the same for this case as for the HVO case above.

In addition, it would, through free attribution, be possible to attribute all biogenic content of the raw material to the production of, for instance biofuel, while the fossil carbon content was attributed to the production of carbon black (and to the remainder of pyrolysis oil produced). The total amount of products attributed to bio-based raw materials could not be larger than what could be produced (taking losses into account), based on the total amount of bio-based raw material used. In addition, products that is not possible to produce from bio-based raw material (such as, e.g., steel scrap) can of course not be attributed to this material.

It would also be possible to use a RED II verification scheme (e.g., ISCC EU) to certify 48% of the pyrolysis oil as based on bio-based raw material and sell this to refineries for the production of advanced biofuel. And to use an MBC scheme (e.g., ISCC PLUS) to certify the remainder of the pyrolysis oil (together with carbon black) to sell as a recycled product for, e.g., the chemical industry.

13 CONCLUDING REMARKS

This work focusses on three different frameworks that can be used for estimating the environmental performance of products and in particular transport fuels: the Renewable Energy Directive (RED II), Environmental Product Declarations (EPD) and Product Environmental Footprint (PEF). It is clear that the different frameworks have different scope and can be used for different purposes. As such they can all be considered relevant to be used by fuel producers although in different contexts. RED II is a commonly applied method and highly linked to regulatory measures in the EU. The scope of RED, however, is limited to GHG emissions. With increased need for holistic approaches and to avoid problem-shifting situations, additional environmental parameters shall be included; thus, the need for applying a broader LCA framework increases. Moreover, as the LCA field develops and other sectors tend to customize their LCA tools and modelling approaches (such as the construction sector), fuel producers may need to provide data that are specifically adapted to certain LCA frameworks such as EPD or PEF.

Based on the work performed in this project and the results obtained it can be concluded that applying all three frameworks is not a straightforward task. The methods contain fundamental differences and are at different levels of development, maturity, and adoption. In certain situations, they can lead to conflicting results, thus influencing decision making processes in different directions. Understanding the differences and underlying assumptions can be important for understanding the variations in outcome.

Moreover, the study confirms that applying a framework like EPD or PEF in addition to RED II would require significant supplementary efforts – not only because of different rules (which were often contradicting or difficult to interpret) but also because of additional data and reporting requirements. The need for expertise and resources is increasing for fuel producers to be able to provide EPD and PEF compliant assessments.

In this study, we also investigated the relationship between the LCA frameworks and schemes for chain of custody certification (CoCC), in particular schemes for mass balance certifications (MBC) to investigate to what extent these schemes complement or overlap with LCA.

Specific conclusions and recommendations from this work are listed below.

13.1 CONCLUSIONS FROM THE META-ANALYSIS OF THE RESULTS

The results obtained for a specific fuel could differ substantially depending on the framework applied and the assumptions and interpretations made when applying this framework. Certain methodological parameters were identified to have a greater impact on the results than others. In short:

- The three frameworks diverge in how waste management is modelled (see Section 11.1). This is important for the results when the fuel is produced from waste.

- The frameworks diverge in what approaches are allowed for modelling processes with multiple products (Section 11.2). This can be very important for the results when the fuel is co-produced with other products.

- The frameworks also diverge in how the electricity supply is modelled (Section 11.3). This is not very important for the results in most of our case studies, because the production of these biofuels does not require a lot of electricity.

The PEF guidelines, in particular the Circular Footprint Formula (CFF), that guides the modelling of material production and waste management, proved a challenge to interpret. The CFF is designed to give clear and specific methodological guidance, and the PEF guide gives support in much of the interpretation of the formula (European Commission 2018b pp. 113-130); however, a couple of aspects of the CFF need further consideration. Examples identified in this work include the distinction between energy recovery and material recycling, the definition of the specific factors included in the CFF, the point of substitution etc.

PEF Category Rules (PEFCR) for biofuels would probably improve the situation by focusing on identifying points of substitution that are specific for biofuels. We recommend that the industry develops a PEFCR for biofuel with support from experts on PEF and on LCA in general.

In a similar manner, Product Category Rules (PCR) for biofuel would help making the EPD methodology more well-defined to clarify, for example, how to partition burdens in the most important multifunction processes. A biofuel PCR could also more clearly establish whether emissions from digestions should be included in an EPD of biogas (as indicated by Version 3.01 of the General Programme Instructions) or excluded from the EPD (as indicated by Version 4.0 and by the PCR for electricity and heat). We recommend that the industry develops such a PCR with support from experts on EPD and on LCA in general.

13.2 LCA IN A BROADER PERSPECTIVE

The conclusions and reflections when the investigated frameworks are compared to mass balance certification (MBC) schemes can be summarized as follows:

- The purpose of MBC schemes and LCA are different, in the sense that the first aim at verifying the sources and sustainability of total amounts of raw materials used by tracking them throughout the value chain, while the second at quantifying specific environmental impact. The system boundaries are similar, since both cover the entire value chain, but may be applied differently depending on the detailed frameworks applied and choices made in applying the MBC schemes.

- The application of MBC schemes and LCA are rather sequential, or depending on each other, than overlapping in their focus. The purpose of the MBC (or other CoCC) schemes is to provide reliable data on raw material used for the value chains connected to the production of specific products in a specific process (or processes) located at specific production sites. LCA is then used to quantify environmental impact from these value chains. Especially, when GHG emissions are included in the certification, LCA is *required* as a tool for quantifying these emissions.

- In general, the MBC schemes proclaim that emissions should be calculated either according to RED or to LCA standards, but the choice of method is not specified. This means that the calculations could in principle use either of the frameworks included in this study.

- When using LCA to quantify GHG emissions within MBC schemes, the freedom is larger – compared to the RED II regulations – in relation to the choice of data sources, the physical properties on which allocation is based and averaging of data. The difference in result should in most cases be relatively small.
- The major difference is the possibility to, under certain conditions, freely attribute the bio-based raw material between products, thereby impacting both the amounts of products that are available (on a specific market) and their communicated specific GHG data. Total emissions reported, from the companies' entire production, is not impacted by such attributions but the market value of different products may be.

13.3 RECOMMENDATIONS

To enhance the development and harmonization of studied LCA approaches this project stresses the need for product specific rules (in the form of PEFCR and PCR) for renewable fuels.The variety of promising feedstock alternatives in biofuel production (industrial residues, waste, electricity, or other type of energy carriers) indicate that future transport fuels are likely to involve complex and interconnected (circular) value chains making the need for updated and comprehensive rules of paramount importance.

Future versions all three studied frameworks should be clearer on how specific methodological choices are to be applied (e.g., when it comes to allocation and multifunctional processes) as well as when it comes to model electricity supply. RED for example shall be clearer on how to define the electricity region while EPD guidelines on how to define the electricity market.

Although it is not realistic to aim for a single unified LCA framework, the biofuel PCR and PEFCR can be developed with RED in mind. Some aspects of the PEF methodology can perhaps also be integrated into RED III. This would enhance the broader adoption of the frameworks among fuel producers.

Finally, the involvement and engagement of the industry, and fuel producers themselves is very important. A recently finalised project on the application of PEF and EPD on paper and steel products stressed also the benefits of industry engagement not only in terms of capacity building and increase awareness but also in terms of preparedness for future developments and requirements (Palander *et al.*, 2021). The actors involved in that project identified similar methodological and data challenges as the ones described in this report. Industry initiatives are therefore essential for the development of biofuel PCR and PEFCR while the general development of the three frameworks can also be influenced.

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APPENDIX

Circular Footprint Formula (CFF)

The CFF can be divided into three parts: material+ energy +disposal:

Material: $(1-R_1)E_v + R_1 \times \left(AE_{recycled} + (1-A)E_v \times \frac{Q_{sin}}{Q_p}\right) + (1-A)R_2 \times (E_{recyclingEoL} - E_v^* \times \frac{Q_{sout}}{Q_p})$

Energy: $(1-B)R_3 \times (E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec})$

Disposal: $(1-R_2-R_3) \times E_D$

Definitions of the parameters presented in the CFF are obtained from the PEFCR guidance v.6.3 (European Commission, 2018) and are shown below.

A: allocation factor of burdens and credits between supplier and user of recycled materials.

B: allocation factor of energy recovery processes: it applies both to burdens and credits.

Qs_{in}: quality of the ingoing secondary material, i.e. the quality of the recycled material at the point of substitution.

Qs_{out}: quality of the outgoing secondary material, i.e. the quality of the recyclable material at the point of substitution.

Qp: quality of the primary material, i.e. quality of the virgin material.

R_1: the proportion of material in the input to the production that has been recycled from a previous system.

R2: the proportion of the material in the product that will be recycled (or reused) in a subsequent system. R2 shall therefore take into account the inefficiencies in the collection and recycling (or reuse) processes. R2 shall be measured at the output of the recycling plant.

R3: the proportion of the material in the product that is used for energy recovery at EoL.

$E_{recycled}$ (E_{rec}): specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled (reused) material, including collection, sorting and transportation process.

$E_{recyclingEoL}$ (E_{recEoL}): specific emissions and resources consumed (per functional unit) arising from the recycling process at EoL, including collection, sorting and transportation process.

E_v: specific emissions and resources consumed (per functional unit) arising from the acquisition and preprocessing of virgin material.

E^*_v: specific emissions and resources consumed (per functional unit) arising from the acquisition and preprocessing of virgin material assumed to be substituted by recyclable materials.

E_{ER}: specific emissions and resources consumed (per functional unit) arising from the energy recovery process (e.g. incineration with energy recovery, landfill with energy recovery, …).

$E_{SE,heat}$ and $E_{SE,elec}$: specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted energy source, heat and electricity respectively.

E_D: specific emissions and resources consumed (per functional unit) arising from disposal of waste material at the EoL of the analysed product, without energy recovery.

$X_{ER,heat}$ and $X_{ER,elec}$: the efficiency of the energy recovery process for both heat and electricity.

LHV: Lower Heating Value of the material in the product that is used for energy recovery.

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