CHALMERS
UNIVERSITY OF TECHNOLOGY

A Comparison of Different Frameworks for Product Environmental Performance

A life-cycle-Based Environmental Assessment of HVO from Used Cooking Oil (UCO) based on EPD, PEF and REDII frameworks
Master’s thesis in Industrial Ecology

CAROLINA JOGNER
PAVINEE NOJPANYA

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
www.chalmers.se
Report No. E2021: 060

REPORT NO. E 2021: 060

A Comparison of Different Frameworks for Product Environmental Performance

A Life-Cycle-Based Environmental Assessment of HVO from Used Cooking Oil (UCO) based on EPD, PEF and REDII Frameworks

CAROLINA. JOGNER
PAVINEE. NOJPANYA

Department of Technology Management and Economics
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021

A Comparison of Different Frameworks for Product Environmental Information
A life-cycle-Based Environmental Assessment of HVO from Used Cooking Oil (UCO) Based on EPD, PEF and REDII frameworks
CAROLINA. JOGNER
PAVINEE. NOJPANYA

© CAROLINA. JOGNER, 2021.
©PAVINEE. NOJPANYA, 2021.

Supervisor: Tomas Rydberg, Sofia Poulikidou
Examiner: Henrikke Baumann

Report no. E2021: 060
Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 (0)31-772 1000

Gothenburg, Sweden 2021

A Comparison of Different Frameworks for Product Environmental Information
A life-cycle-Based Environmental Assessment of HVO from Used Cooking Oil (UCO) Based on EPD, PEF and REDII frameworks

CAROLINA. JOGNER
PAVINEE. NOJPANYA

Department of Technology Management and Economics
Chalmers University of Technology

Summary

In this project, Product Environmental Footprint (PEF), Environmental Product Declaration (EPD) and the recast of the Renewable Energy Directive (REDII) framework were assessed and compared through the application on the case study of Hydrotreated Vegetable Oil (HVO) from Used Cooking Oil (UCO). The case study is part of the Impacts on Fuels Producers and Customers of Conflicting Rules for LCA (ICON) project to gain a deeper understanding on the differences between different environmental frameworks. The assessment was done based on the life cycle of the UCO-based HVO. The applied functional unit was 1 MJ of the studied HVO used by a heavy-duty truck (Euro V). The UCO was assumed to be a mixture of palm oil and rapeseed oil. The impact category that was chosen to be assessed was climate change as it was the only impact category the three frameworks have in common.

The results show that there are differences between the PEF, EPD and REDII frameworks, which led to different results. The highest impact (51.3 g CO_2-eq) was obtained when the PEF framework was applied and the REDII frameworks gave the lowest impact (11.9 g CO_2 -eq). The results in EPD and REDII shows 70% and 77% respectively lower impact compared to the PEF. The observed differences between the frameworks were the choice of allocation method when secondary material was used, allocation hierarchy for multifunctional processes, the assessed number of elementary flows and impact categories, the CFs, the accounting of biogenic CO_2 and the downstream process. The upstream processes gave the highest contribution to the results in PEF, while for the EPD and REDII it was the hydrogen production. In addition, the UCO collected in Sweden was the most environmentally preferred alternative compared to UCO from China. However, the lack of a specific ruleset such as PEF Category Rules (PEFCR) and EPD's Product Category Rule (PCR) for biofuels may affect the reliability of the results in this case study.

Keywords: product environmental footprint, environmental product declaration, renewable energy directive, hydrotreated vegetable oil, used cooking oil, circular footprint formula, life cycle assessment

Sammanfattning

I detta projekt jämfördes miljöavtryck (PEF), miljövarudeklaration (EPD) och det omarbetade förnybartdirektivet (REDII) genom att tillämpas på en fallstudie om hydrerad vegetabilisk olja (HVO) från använd matolja (UCO). Fallstudien är en del av Impacts on Fuels Producers and Customers of Conflicting Rules for LCA (ICON)-projektet med syfte på att få en djupare förståelse för skillnader mellan de olika ramverken. Beräkningen för de tre olika ramverken baserades på livscykeln för HVO från UCO. Den funktionella enheten valdes till 1 MJ av HVO som används i en tung lastbil (Euro V). UCO:n antogs vara en blandning av palmolja och rapsolja. Miljöpåverkanskategorin som valdes var klimatförändring eftersom det är den enda miljöpåverkanskategorin som de tre ramverken har gemensamt.

Resultaten visar att det finns skillnader mellan PEF-, EPD- och REDII-ramverken som leder till olika resultat. Den högsta påverkan (51,3 g CO_2-eq) erhölls när PEF-ramverket applicerades. REDII-ramverket gav den lägsta påverkan (11,9 g CO_2-eq). Resultaten i EPD och REDII visar 70% respektive 77% lägre påverkan jämfört med PEF. Följande skillnader mellan ramverken observerades: valet av allokeringsmetod när sekundärt material användes, allokeringsgshierarkin för multifunktionella processer, antalet elementära flöden och antal miljöpåverkanskategorier som ramverken tar hänsyn till, kategoriseringsfaktorer och hur biogent CO_2 och nedströmsprocesser redovisas. Uppströmsprocesserna gav högst bidrag till resultatet i PEF, medan vätgasproduktionen var det som bidrog mest i EPD och REDII. UCO som samlats in i Sverige var det mest miljövänliga alternativet jämfört med UCO från Kina. Bristen på ett specifikt regelverk så som PEF beräkningsregler (PEFCR) och EPD:s produktspecifika beräkningsregler (PCR) för biodrivmedel kan påverka tillförlitligheten på resultaten i denna fallstudie.

Acknowledgment

We would like to thank our supervisors Sofia Poulikidou and Tomas Rydberg at IVL Swedish Environmental Research Institute for all the guidance and support throughout our project. Your valuable feedback has helped us to improve our work enormously. We would also like to thank the ICON-project team, especially Tomas Ekvall who has saved us many times with his expertise.

We would like to thank Katarina Persson from Preem, who has provided us with interesting insights on the HVO production processes.

Lastly, we would like to thank our families for the support and the endless cups of tea whenever we needed it.

Carolina Jogner, Pavinee Nojpanya, Gothenburg, May 2021

Table of Contents

List of acronyms

ALCA	Attributional Life Cycle Assessment
CF	Characterization Factor
CFF	Circular Footprint Formula
CLCA	Consequential Life Cycle Assessment
CPA	Classification of Products by Activity
CPO	Crude Palm Oil
dLUC	Direct Land Use Change
DQR	Data Quality Rating
EC	European Commission
EoL	End of Life
EPD	Environmental Product Declarations
FAME	Fatty Acid Methyl Ester
GPI	General Programme Instructions
GHG	Greenhouse Gas
GWP	Global Warming Potential
HVO	Hydrotreated Vegetable Oil
HFO	Heavy Fuel Oil
ILCD	International Reference Life Cycle Data system
iLUC	Indirect Land Use Change
ISO	International Organization for Standardization
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LHV	Lower Heating Value
LUC	Land Use Change
LULUC	Land Use and Land Use Change
NACE	Nomenclature Générale des Activités Economiques dans les Communautés Européennes
NG	Natural Gas
PCR	Product Category Rules
PEFCR	Product Environmental Footprint Category Rules
PEF	Product Environmental Footprint
PFAD	Palm Fatty Acid Distillate
PO	Palm Oil
PPP	Polluter Pays Principle
REDII	Renewable Energy Directive
RPO	Refined Palm Oil
RS	Rapeseed
RSO	Rapeseed Oil
UCO	Used Cooking Oil

1. Introduction

With increasing concerns over the environmental impacts of human consumption, several methods have been developed in an attempt to assess and quantify those impacts. A life cycle perspective has become a prevalent approach as it takes into consideration the environmental loads of a product or service throughout its lifetime. Having information on the environmental performance of their products is important for companies in terms of regulatory compliance, decision support and marketing. However, since different frameworks may suggest different accounting methodologies, it is useful to understand how these methodologies affect the result of product’s performance.

In this project, three environmental assessment frameworks are studied and compared when applied a particular product. The studied product is Hydrotreated Vegetable Oil (HVO) where Used Cooking Oil (UCO) is used as feedstock; the analyzed considered in this work are: Product Environmental Footprint (PEF), Environmental Product Declaration (EPD) and the recast of the Renewable Energy Directive (REDII) required by the European Union (EU).

1.1 Background

This master thesis is conducted as a part of the ICON project. ICON stands for ***I**mpacts on Fuels Producers and Customers of **Con**flicting Rules for LCA*. The project is funded by the Swedish Energy Agency through the f3 centre (Swedish Knowledge Centre for Renewable Transportation Fuels) for renewable fuels. The project consortium consists of research institutes, universities and industry.

The aim of the ICON project is to increase the understanding of different calculation methodologies that exist within different frameworks and how different frameworks influence the obtained results. The intended audience are the transportation fuel industry, researchers and policy makers. The different frameworks may have different rules, purposes and preconditions to account for a product’s environmental impact. As the rules are not harmonized with each other the environmental assessment frameworks are not equally comparable.

1.1.1 Product Environmental Footprint

The Product Environmental Footprint (PEF) is a method that uses a life cycle approach to assess and quantify environmental impacts of goods or services (EC, 2018). The method is developed in 2012 by the European Commission as part of the Recommendation 2013/179/EU. The purpose of the PEF is to be used as a common and harmonized approach to measure and communicate the environmental impact of products and services. The PEF framework is adapted by taking into consideration various recognized environmental assessment guidance documents such as the ISO14000 series standards, ILCD (International Reference Life Cycle Data system) Handbooks and Ecological Footprint.

When a comparison between products is to be made, a Product Environmental Footprint Category Rule (PEFCR) is required. PEFCRs provide the rules on how to carry out the assessment of products within the same category at process and/ or product level (EC, 2018). The use of PEFCR increases reproducibility, quality, consistency and relevance of the PEF study. Despite being initiated in 2012, the PEF framework is still under development in a so called “transition phase” (Drost, 2020). During the transition phase, several PEFCRs for different product categories have been developed and tested. However, a PEFCR for biofuel is currently not available. It is said that the PEF will enter the “*implementation & communication phase*” in 2021 (Drost, 2020).

1.1.2 Environmental Product Declaration

The Environmental Product Declaration (EPD) is used as an environmental communication tool in market situations. It provides transparent information about the environmental impact of a product over its entire life cycle (EPD International, 2019). The framework is based on a Life Cycle Assessment (LCA) that follows Product Category Rules (PCR). The PCR acts as a guideline for how the EPD should be conducted for a specific product category. The rules enable different practitioners to generate consistent results that allows comparison of the environmental impact between products that provide the same function. A PCR is developed after the ISO/TS 14027 (EPD International, 2019). It acts as a complement to the General Programme Instructions (GPI) on how an EPD should be conducted, which follows the ISO 14025 Environmental labels and declarations – Type III environmental declarations.

The EPD framework has a similar structure as the general LCA methodology (ISO 14040/14044), with some preconditions found in the PCR for the product category (EPD International, 2019). However, currently there is no PCR for biofuels so the general framework of EPD was followed in this study.

1.1.3 The Recast of Renewable Energy Directive

The recast of Renewable Energy Directive 2018/2001/EU i.e. REDII is implemented with the ambition of reducing the greenhouse gas (GHG) emissions in order to meet the Paris Agreement and maintaining its leading position on renewable energy (EC, 2021). The REDII is part of the Clean Energy for all Europeans package and was based on the original Renewable Energy Directive 2009/28/EC. In the updated version the total renewable energy consumption target was raised from 20% to 32%, which is to be achieved by 2030 (EC, 2021). For transportation biofuels producers, the biofuels that is produced after January 2021 need to reach an emission reduction of 65% when comparing to emission that would arise from the use of fossil fuel (EC, n.d.). The term biofuel is defined according to the REDII as *"liquid fuel for transport produced from biomass*".

The REDII framework is not an LCA framework, but it has a life-cycle-based approach when considering the emissions of transportation biofuels, renewable fuels and electricity heating and cooling. The REDII framework is used for reporting regulatory compliance, thus plays an important role in company's decision making.

1.1.4 Hydrotreated Vegetable Oil

The ICON project investigates the differences between the three mentioned frameworks through application on case study for different types of fuels, HVO from UCO being one of them. HVO is a type of paraffinic biobased liquid fuel (Arvidsson et al., 2011). The chemical structure of the HVO is C_nH_{2n+2} which is almost identical with traditional fossil-based diesel. This makes HVO compatible with the conventional diesel as the chemical properties are almost the same. The feedstock for HVO biodiesel is very flexible and can originate from a wide range of fats and oils, e.g. animal waste and vegetable oils including UCO. In this study, UCO is referred as a mixture between different type of used vegetable cooking oils. The possibility to use already existing vehicles and infrastructure is a great advantage and makes HVO a fuel that is easy to implement on the market.

The HVO considered in this study is produced in Preem's refinery in Gothenburg. UCO is bought on the market and consists of different types of used vegetable oils that have been collected from the food industry and restaurants. Oil collection for further use is beneficial as the oils can cause problems in the sewage systems and contains a lot of energy that can be utilized further as for example a transport biofuel. UCO can also be used in a wide range of products like soap, chemicals and stearin (Karlsson et al., 2020).

The domestic supply of UCO in the EU is not enough to meet the demand and therefore a large part of the UCO used in the EU originates from Asia (Phillips, 2019). Due to different climate conditions the oilseed crops that are cultivated differs between Europe and Asia (Phillips, 2019). This means that the content of UCO may differ in different continents. In Asia palm oil is the dominating oil while in Europe rapeseed oil is more common (Phillips, 2019). This makes the origin of the UCO important as different oils have different properties and production routes.

1.2 Aim and objectives

The overarching aim of this master project is to study and compare three environmental frameworks: PEF, EPD and REDII. The comparison is achieved by using a case study on HVO from UCO where the three frameworks are applied.

In addition, the project aims to provide more information on the environmental impact of the HVO where two different origins of UCO are compared in order to identify the most environmentally preferred alternative. This independent aim is intended to be used by Preem and other biofuel producers.

The following objectives are to be fulfilled:

- Present and analyze the three different frameworks regarding their modelling and accounting methodologies.
- Apply the frameworks to the case study.
- Identify, present and discuss differences in the results as a consequence of methodological variations of the different frameworks.
- Identify the life cycle stage that has the greatest environmental load according to the three frameworks.
- Identify and present differences in the results as a consequence of variations in the origin of UCO.
- Provide recommendations for fuel producers on which origin of UCO is the most environmentally preferred as well as provide relevant insights to the ICON project.

1.3 Delimitations

The study focuses on the production of HVO originating from UCO. Thus, other feedstocks such as virgin vegetable oil or slaughter waste are not considered. The production of HVO takes place at Preem's refinery in Gothenburg, Sweden. The collection area of UCO is delimited to Sweden and China. The cooking oils considered in the UCO is limited to palm oil and rapeseed oil, which are two of the most commonly used cooking oils (Shahbandeh, 2021a).

The environmental assessment is done only on the impact category "Climate Change". The other impact categories required by PEF and EPD are not considered in this project. In addition, only the parts relevant to the calculation methodology in each framework were used. This means that some requirements in the frameworks that do not affect the calculations of the environmental impact were omitted, for example the goal definition, screening process for PEF, the data quality assessment, some parts of the data interpretation and the critical review.

2. Method

In order to compare different environmental assessment frameworks, a literature study of the official guideline documents of each framework can be done. Through close reading, a qualitative description of the similarities and differences between the three frameworks can be found. However, it does not provide practical information such as to what extent and what magnitude the difference in accounting methodologies would result in different environmental impacts when the frameworks are applied to the same product. A case study is therefore needed to gain a deeper understanding of the implications that each framework has in practice. In this work, the PEF, EPD and REDII framework were applied to assess the environmental impact of HVO from UCO.

The research strategy followed to fulfill the aims and objectives of this study can be divided into four parts:

1. A review and analysis of the PEF, EPD and REDII methodologies using official documents, in which key methodological related features of the methods are presented. These include: allocation approach, accounting of carbon stock, system boundary and environmental impact assessment models as defined for each model (PEF, EPD and REDII).

2. Inventory of the HVO production from UCO and mapping of materials and energy flows from a life cycle perspective i.e. from the cultivation of raw materials to the use phase. This was to learn about the processes in the studied system and to understand what is needed to produce HVO from UCO. The obtained data were used as common inventory data for the environmental impact assessment in all three models according to their defined system boundaries.

3. Application of the three frameworks to the case study where specifications such as allocation approaches, accounting of carbon stock, system boundary, and environmental impact assessment models were defined for each model (PEF, EPD and REDII).

4. Modelling of the product systems and calculation of the environmental impact according to the three frameworks. The software program OpenLCA was used to model the different product systems. The results were then quantitatively compared in terms of GWP and emissions of CO_2 equivalents. In each framework, the process that contribute to the total environmental impact the most was identified to gain a deeper understanding in the differences between the results. In addition, the environmental impact of the HVO from UCO collected in Sweden and China was done in order to identify which alternative is the most environmentally preferred.

2.1 Official documents of frameworks

As mentioned, official documents were used in order to study the three frameworks. For the PEF framework, the documents were obtained from the European Commission (EC). The documents include the PEF Guide (EC, 2012) and the Product Environmental Footprint Category Rules (PEFCR) Guidance Version 6.3 (EC, 2018). The PEF Guide was used as a general guideline of the structure and procedure of the PEF. The PEFCR Guidance was used to complement the general guideline. The PEFCR Guidance was also used as the main source of information in this study as it contains more specific detail and more updated information regarding the rules and calculation method.

For the EPD framework, the information was obtained from the General Programme Instructions (GPI) for the International EPD® System version 3.01, available in Annex A: General application of LCA methodology (EPD international, 2019). As there is no PCR for biofuels the GPI v.3.01 was used as the main source of information. While this case study was conducted, a new version of the GPI (GPI v.4.0) for the EPD framework was launched. However, as the study was ongoing, it was decided upon continuously use of the GPI v.3.01. Further evaluation will be required to assess if GPI v.4.0 will influence the results.

The REDII framework was studied by using the recast of Renewable Energy Directive (EU) 2018/2001.

3. Study of frameworks

This section describes the requirements, calculations, and modelling methodologies specified in the PEF, EPD and REDII frameworks. Throughout this section, the sources of the data used are the same as the ones described in section 2.1 if not otherwise specified. Lastly, a summary of the comparison of the three frameworks is presented.

3.1 Functional unit

In the PEF framework, the functional unit is called a *unit of analysis*. It shall be defined with regard to a function or a service the product provides, quantity, level of quality, duration or lifetime of the product and also a NACE (Nomenclature Générale des Activités Economiques dans les Communautés Européennes) code which is a code that classify the European economic activities. The NACE code is related to Classification of Products by Activity (CPA), which represent a product’s life cycle. In addition, a reference flow shall be defined in relation to the unit of analysis and the quantitative input and output data collected shall be collected in relation to this flow.

In the EPD framework, a functional unit is commonly defined in the PCR. The functional unit should describe the function of the product in SI units. The information about the technical lifetime or reference service life of the product shall be taken into consideration in the functional unit if possible. A *declared unit* is used instead of a functional unit when the precise function of the product is in some way unknown, or the products final use is undeclared. Since there is no PCR for biofuels, a functional unit is not available.

The functional unit specified in the REDII framework is 1 MJ of fuel.

3.2 System boundaries

The life cycle stages that shall be included in the PEF framework are the extraction processes of raw materials, production, distribution, storage, use phase and end-of-life treatment of the product. In other words, a cradle-to grave life cycle shall be defined as the system boundary. Any deviation from the default cradle-to-grave approach shall be explicitly specified and justified in a PEFCR. Since the PEF’s system boundary covers the environmental impact from the cradle to the grave, agricultural activities are relevant. The PEF framework has specific requirements that need to be followed in order to model agricultural activities. See Appendix A (part 1) for details.

For an LCA that will act as a base for the EPD, all processes from cradle-to-grave are normally included within the system boundaries. The EPD’s life cycle of the product is divided into three different life cycle stages, the upstream processes, the core processes and the downstream processes. This is for the purpose of result presentation and because different life cycle stages have different requirements on data quality. According to the EPD framework, upstream process refers to processes that produce input to the core processes (cradle-to-gate). Core process refers to the manufacturing of the studied product, in which the processes are managed by the organization the EPD is issued for (gate-to-gate). Downstream process refers to use stage and end-of-life stage of the product (gate-to-grave). Any specific system boundary that should be used for a product is further defined in the PCR for that product category.

For the REDII the default system boundary starts at the extraction or cultivation phase for raw materials and ends at the use phase of the fuel.

3.2.1 Time boundaries

The PEF framework states that the required data over the cultivation phase shall be collected over a timespan that is enough to provide an average assessment. For annual crops, the assessment period must be at least three years. If the data is not available due to the new production system, the timespan can be shorter but should not be less than one year. For perennial plants, the data used must be at a steady state. In other words, it should represent all the development stages involved in the studied period. The time boundary for the EPD framework shall express the time period for which the inventory is accounted for. No specifications for time boundaries are mentioned in REDII.

3.2.2 Boundaries within the technical system

Within the technical system, it is relevant to discuss about capital goods and the cut-off criterion applied by each framework. Capital goods refer to buildings, machinery, infrastructure and vehicles. The PEF guide considers capital goods to be included in the calculation. However, a publication by European Commission’s Joint Research Centre (JRC), suggests some changes in the PEF method. One of these changes is the exclusion of the capital goods from the calculation, unless there is evidence to support that the capital goods are relevant to the system (Zampori & Pant, 2019).

For the EPD, a PCR would provide guidelines whether capitals goods are to be considered in the calculation or not. Since there is no PCR for biofuels, the inclusion of the capital goods cannot be concluded. However, by reviewing the PCR 2020:05 Basic products from forestry version 1.0, it can be concluded that the manufacturing of production equipment, buildings and other capital goods shall not be included. The REDII states that *“emissions from manufacture of machinery and equipment shall not be taken into account”*.

Regarding the cut-off criteria, the PEF does not allow any cut-off during a screening process. The screening process is a preliminary study, which is done in order to identify the most relevant processes, elementary flows, impact categories etc. This means that the whole life cycle needs to be modelled. After the screening step, a process can be excluded if it contributes less than 1% of the total environment impact for each impact category. This cut-off criterion is also applied to the process where its contribution is less than 1% for all impact categories except for human toxicity (cancer and non-cancer effect) and freshwater ecotoxicity.

For the EPD, the maximum cut-off is 1% of the total environmental impact. For the REDII, all the emissions resulting from the processes that are required according to the GHG emissions formula must be included. Thus, no cut-off criterion is specified.

3.3 Different types of LCA

There are two main types of LCA, attributional LCA (ALCA) and consequential LCA (CLCA). ALCA is used when the aim is to understand the share of the global environmental impact that is related to the life cycle of a product. An attributional type of LCA often have a retrospective point of view and is used to compare existing products. The aim of a CLCA is to estimate the change in the environmental impact as a result of the life cycle of a product. CLCA has a prospective view and is a useful tool in product development (Baumann & Tillman, 2004). The two types answer different questions and often give different results depending on the different preferred allocation methods, choice of data and where the system boundaries are drawn. If the distinguish between the two types is not clearly made the result obtained may be misinterpreted and can result in an unfair comparison between different studies (Brander et al., 2008).

EPD belongs to the attributional type of LCA and it is specifically stated that the data should be specific or average to be able to trace and control the data. The RED II quantifies the emissions from renewable energy and reflect the effect of a change. The REDII looks at the change in environmental impact, which indicates a character of a CLCA. However, the REDII framework uses average data, and the result is compared to fossil fuel, which makes the REDII framework mainly have elements of ALCA. PEF is a combination of ALCA and CLCA as it takes features from both. PEF allows average data to be used which is in line with an ALCA, but it also allows system expansion which is a prioritized allocation strategy in an CLCA but not recommended in an ALCA.

3.4 Allocation

An allocation problem occurs when a process has multiple inputs, multiple outputs or involves recycling, reuse or recovery of materials. The three frameworks provide the following approaches for dealing with the allocation problem.

3.4.1 Multifunctional processes

To deal with multifunctional processes in PEF, a decision hierarchy is applied as followed: i) avoid allocation by subdivision or system expansion ii) allocation based on relevant physical relationship iii) allocation based on other relationship e.g. economic value. While the definitions of system expansion can vary, the term in the PEF context refers to “expanding the system by including additional functions related to the co-products" (EC,2018). System expansion can also refer to the substitution approach where the co-product substitutes a product with the same amount in another equivalent process. The credit from substituting the co-product is then attributed to the original process. According to the ISO14044, the substitution approach is described as an approach to avoid allocation. However, this is conflict with the PEF’s definition as the substitution is referred as an alternative approach in the second step of the hierarchy i.e. allocation based on relevant physical relationships.

The EPD framework suggests similar hierarchy but with system expansion approach excluded. System expansion is not applicable because the framework is strictly ALCA. Thus, the EPD’s allocation rules are presented as followed: i) avoiding allocation if possible, by “*dividing the unit processes to be allocated into different sub-processes and collecting the input and output data related to these sub-processes.”* ii) if allocation cannot be avoided, the partitioning of input and outputs between products/functions should be based on the underlying physical relationships between them iii) if physical relationship cannot be applied as basis for partitioning, other relationships can be used.

For the REDII, the GHG emissions are to be allocated between the biofuel and the co-products in relation to their energy content. Lower heating value (LHV) can be used to determine the energy content of the co-products other than electricity and heat. In case that there is cogeneration of electricity and heat, the GHG emissions shall be allocated between the electricity and useful heat based on temperature of the heat. The temperature indicates the usefulness of the heat. The usefulness of heat can be found by multiplying the energy content with the Carnot efficiency, C_h. The value of C_h is calculated according to the Equation 1.

$$C_h = \frac{T_h - T_0}{T_h} \qquad \text{(Equation 1)}$$

The T_h is the temperature (in Kelvin) of the useful heat at point of delivery and the T_0 is the temperature of surrounding, which is set at 273.15 K.

However, it is stated in the REDII that substitution can also be used as an appropriate allocation approach in the case of policy analysis.

3.4.2 Recycling, reuse and recovery

When a material from one product is recycled, reused or recovered into another, it creates an allocation problem. This is because the material is used in several products, and it is not always clear how the impact of the secondary material shall be defined.

There is a discrepancy in how the allocation problem shall be handled between different frameworks. The PEF framework looks at the primary material and its upstream impact as a burden and the use of the secondary material is considered as a benefit. It also takes into account the burden and benefits of energy recovery. The PEF's accounting method of this allocation problem is called Circular Footprint Formular (CFF). The CFF is a formula that combines several parts into consideration, which consist of i) the use of virgin material ii) the use of recycled material iii) recycling of the material after use iv) energy recovery from waste material and v) disposal of waste material (T. Ekvall, personal communication, March 9, 2021). The five modules that form the CFF is shown in Equation 2-6 (EC, 2018).

i) Burden of production:

$$(\mathbf{1}-\boldsymbol{R}_{\mathbf{1}})\boldsymbol{E}_{\boldsymbol{V}}+\boldsymbol{R}_{\mathbf{1}}\times\boldsymbol{E}_{\boldsymbol{recycled}}) \qquad \text{(Equation 2)}$$

ii) Burdens and benefits related to secondary materials input:

$$-(\mathbf{1}-\boldsymbol{A})\boldsymbol{R}_{\mathbf{1}}\times(\boldsymbol{E}_{\boldsymbol{recycled}}-\boldsymbol{E}_{\boldsymbol{V}}\times\frac{Q_{sin}}{Q_P}) \qquad \text{(Equation 3)}$$

iii) Burdens and benefits related to secondary materials output:

$$(\mathbf{1}-\boldsymbol{A})\boldsymbol{R}_{\mathbf{2}}\times(\boldsymbol{E}_{\boldsymbol{recyclingEoL}}-\boldsymbol{E}_{\boldsymbol{V}^{*}}\times\frac{Q_{sout}}{Q_P}) \qquad \text{(Equation 4)}$$

iv) Energy recovery:

$$(\mathbf{1}-\boldsymbol{B})\boldsymbol{R}_{\mathbf{3}}\times(\boldsymbol{E}_{\boldsymbol{ER}}-\boldsymbol{LHV}\times\boldsymbol{X}_{\boldsymbol{ER,heat}}\times\boldsymbol{E}_{\boldsymbol{SE,heat}}-\boldsymbol{LHV}\times\boldsymbol{X}_{\boldsymbol{ER,elec}}\times\boldsymbol{E}_{\boldsymbol{SE,elec}}) \qquad \text{(Equation 5)}$$

v) Disposal:

$$(\mathbf{1}-\boldsymbol{R}_{\mathbf{2}}-\boldsymbol{R}_{\mathbf{3}}) \times \boldsymbol{E}_{\boldsymbol{D}} \qquad \text{(Equation 6)}$$

The A factor shows the allocation of the burdens and benefits between two life cycles, and it is intended to reflect the current market situation. The A factor for different materials can be found in Annex C in the PEFCR guidance v.6.3 and the value of the A factor can be 0.2, 0.5 or 0.8. In the case where the A value is not available, factor 0.5 should be used.

The B factor is an allocation factor for energy recovery processes, which applies both to burdens and credits. The E-value refers to specific emissions and resource consumed arising from different sources for example from the acquisition and pre-processing of virgin material (E_v), from the recycling process of the recycled/reused material ($E_{recycled}$ or E_{rec}) etc.

The R-factor reflect the proportion of the recycled/resued material in different sequence of use of the material. For example, R1 is the proportion of the input of the material that has been recycled for the first time from the previous system, R2 refers to the proportion of the recycled material that will be used in the subsequent system and R3 is the proportion of the material that is used for the energy recovery at End-of-Life (EoL).

The Q-value represent quality of material: Qp for the primary material, Qsin for the ingoing secondary material at the point of substitution i.e. the point where the secondary material substitute primary materials. The PEFCR guidance suggests that the quality can be quantified by economical aspect such as price ratio. The quality ratio shall be set to 1 in case that the price of the secondary material is higher than the primary material. The X factor refers to the efficiency of the energy recovery process for heat and electricity. LHV refers to lower heating value of the material that is used for recovery of energy.

However, the whole CFF may not necessary be applied but rather depending on the situation of the waste handling in the life cycle of the product of interest.

The EPD framework on the other hand applies Polluter Pay Principle (PPP) to the allocation problem that is related to waste. The PPP means that the polluters should bear the expense of preventing and controlling the emissions caused by their products (OECD, 1972). According to the EPD, the point at which the waste has its “lowest market value” is the point where two product system can be delineated. Applying the PPP to this delineation, it means that the waste generator (the polluter) shall bear all the environmental impact until the point where the waste is transported to scrapyard or collection site. This allocation approach in the EPD means that the burden of the upstream of the recycled material is not accounted for in the subsequent process.

The REDII does not have any specific method for the recycling or reused of waste. For the case of biofuels and bioliquids, it stated simply that “*Wastes and residues, including tree tops and branches, straw, husks, cobs and nut shells, and residues from processing, including crude glycerine (glycerine that is not refined) and bagasse, shall be considered to have zero life-cycle greenhouse gas emissions up to the process of collection of those materials irrespectively of whether they are processed to interim products before being transformed into the final product*.”

The definition of waste in the REDII was made according to the Waste Framework Directive (2008/98/EC) which is defined as “*any substance or object which the holder discards or intends or is required to discard”*. Hence, the upstream impact of a material that can be considered as waste shall not be included in the total emission of the biofuel or bioliquid in the REDII framework.

3.5 Foreground and background system

The PEF framework requires that the processes included in the system boundaries are to be divided into foreground and background processes. Foreground systems include the processes that are under direct influence of the decision maker, background systems are the processes affected indirectly by the foreground system. Foreground and background systems has less relevance in an ALCA as an ALCA considers all life cycle stages in the system equally (Baumann & Tillman, 2004). Hence, the EPD and REDII which are considered ALCAs have no specific requirement regarding foreground and background system.

3.6 Data specifications

As a general rule in the PEF framework, directly collected and company-specific data should be used in the first hand. If this is not possible, generic data can be used. The data for electricity from the grid consumed upstream or within the defined system boundary shall be supplier-specific data. If this is not possible, then country-specific consumption-mix data shall be used.

The EPD framework divides the system processes into upstream, core and downstream process. The type of data that should be used for each process is normally defined in the PCR of a product. In general, site specific data for the studied process is preferred and must be used in the core and upstream process. If specific data in not accessible for the upstream process, representative generic data can be used. For the downstream processes, data based on scenarios should be used. The data should be expressed as an average over a reference time period.

The REDII framework is a policy document that sets targets for emission reduction. Producers are using the calculations rules within the framework to calculate their product's emission reduction to then report to the authorities. The calculated GHG emissions saving can be classified as actual value, typical value or default value. Actual value is the GHG emissions saving that is calculated by using specific data for specific production processes of biofuels. Typical value refers to GHGs and GHG emissions saving specified in the REDII, which represent the EU's consumption. Default value refers to a derived typical value, which results from the use of pre-determined factors. The default value can be used instead of actual value if it complies with circumstances specified in the directive. Hence, the data used in the REDII framework can be either specific or pre-determined data provided in the Annex V in the REDII.

3.7 Data quality requirement

The PEF framework requires an assessment of data quality that should fulfill the following criteria: technological representativeness, geographical representativeness, time-related representativeness and precision/uncertainty (European Commission, 2017). The framework also requires a review of study and that documentation and use of nomenclature are carried out in compliant with the ILCD framework. The data is assessed by giving a rate for its quality according to each criterion. The overall data quality is then given by a Data Quality Rating (DQR).

Depending on the used data, different EPD's may vary in quality. If this is the case, it is possible to use an indicator to indicate the quality of the data. The indicator shows the percentage of which type of data contribute to the environmental impact. The process is called *data quality declaration*. The level of quality can be found in a specific PCR. The REDII has no specifications on the quality of data used but voluntary schemes can be done to verify and ensure the compliance of the sustainability and GHG emissions saving criteria.

3.8 Selection of environmental impact indicators

In the PEF framework, 16 mid-point impact categories are considered. The default list of the impact categories and the assessment models can be found in Table 2 in the PEFCR guidance. However, all 16 impact categories may not necessary be assessed if they are found to be irrelevant. For the EPD, 7 mid-point impact categories are included in the impact assessment. Normalization and weighting are optional steps which can be done by using predetermined normalization factors and weighting factors for each impact categories. The default EPD impact categories and the recommended assessment model are presented on the International EPD system website. The REDII focuses solely on climate impact based on the GHG emissions which is indicated by CO_2 equivalence in gram. Normalization and weighting can also be done to supplement the result in the EPD framework.

With the limited impact category in the REDII, the result can only be compared with the climate change category in the PEF and the global warming impact category in the EPD. The climate change impact is indicated by radiative forcing calculated as global warming potential over 100 years (GWP100). The GWP100 has a unit of kg CO_2 equivalent (kg CO_2-eq). The GWP100 is assessed according to the IPCC 2013 model. The global warming impact in the EPD also use GWP100 as an indicator but it is to be assessed by using CML 2001 baseline (version August 2016) as an assessment model, which is essentially the same as the IPCC 2013. The requirement for the assessment methods for each framework is described as followed:

3.8.1 Climate change impact – PEF

There are three sub-categories that must be included in the calculation of the climate change impact according to the PEF framework. The sub-categories include land use and land transformation, fossil and biogenic. The three sub-categories characterize the origin of the GHG emissions. The sub-category fossil covers the GHG emissions from the oxidation and/or reduction of fossil fuels, which can result from the combustion, digestion and landfilling. The emission from peat and calcination/carbonation of limestone is also included in this sub-category.

The sub-category biogenic means carbon emissions to air (CO_2, CH_4 and CO) from oxidation and/or reduction of aboveground biomass. It also covers the CO_2 uptake from the atmosphere through photosynthesis of the plant, which can be indicated by the carbon content of products, biofuels or plant residue above ground. The carbon exchanges from native forest, however, are not considered in this sub-category.

The sub-category land use and land transformation covers the carbon uptake and emissions (CO_2, CH_4 and CO) from the change in carbon stock due to land use and land use change. Examples of activities that fall under this sub-category is deforestation, carbon emission from native forests other and soil activities. CO_2 uptake from native forest is to be excluded in the calculation. Land use change can be direct and indirect. Direct Land Use Change (dLUC) is the result of transformation from one land use to another, possibly incurring changes in the carbon stock of that specific land, but not leading to a change in another system. Indirect Land Use Change (iLUC) results from a change in land use that induces changes outside the system boundaries i.e. in other land use types. The PEF only consider dLUC in the calculation and it must occur within a period of 20 years or a single harvesting period. In addition, the PEF Guidance v.6.3 states that calculation of the dLUC is to be done according to the PAS 2050:2011 (BSI, 2011). For the horticultural products, the calculation can be complemented with the guidelines of PAS 2050-1:2012 (BSI, 2012). The iLUC on the other hand, is excluded since the development of the calculation methods is not completed yet.

In addition, the PEFCR guidance states that if a screening process identifies climate change impact as the most relevant impact category, then the result of climate change impact shall be reported as total impact i.e. the sum of the three categories. In addition, if the contribution of the sub-category biogenic and land use and land transformation exceed 5% of the total impact, then the results from both sub-categories shall also be reported separately.

3.8.2 Global warming impact - EPD

When calculating GWP100 (carbon footprint) for EPD, ISO/TS 14087 and PAS 2050:2011 should be used as guidelines. The results should be separately presented both for the upstream, core and downstream processes and as an aggregated impact for the whole life cycle. When calculating, both removals and emissions GHGs from different sources e.g. direct land use and land use change (LULUC), biogenic sources and fossil sources should be included. All sources should be presented separately. If the material is a secondary material that contains stored carbon, the carbon content should be accounted for in the same way as a primary material.

3.8.3 Climate impact – REDII

The REDII uses GHG emissions to assess the climate impact of biofuels. The calculation of the GHG emissions was done according to Equation 7. For more details on each parameter, see Appendix B.

$$E = e_{ec} + e_{l} + e_{p} + e_{td} + e_{u} - e_{sca} - e_{ccs} - e_{ccr} \qquad \text{(Equation 7)}$$

Where:

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

According to the framework, the capture of CO_2 from the cultivation or extraction of raw materials shall be excluded. For biofuels the emissions from fuel in use e_u, shall be counted as zero. The GHG emissions from the waste and residue are considered to have zero GHG emissions up to their collection process. The unit of the GHG emission is predetermined as grams of CO_2 per MJ of fuel (g CO_2-eq/ MJ). The GHGs that are considered in the calculation are CO_2, N_2O and CH_4 and their characterization factors (CFs) are 1, 298 and 25 respectively.

The saving of reduction of the GHG emissions from biofuels can be calculated according to Equation 8:

$$Saving = \frac{E_{F(t)} - E_b}{E_{F(t)}} \qquad \text{(Equation 8)}$$

Where:

E_b = total emissions from the biofuel; and
$E_{F(t)}$ = total emissions from the fossil comparator for transport.

The fossil fuel comparator for transport is the amount of GHG emissions from fossil fuel that must be used to compare with the calculated GHG emissions from the biofuel. The fossil fuel comparator is determined to be 94 g CO_2eq/MJ.

Since there is only one impact category that all three of the frameworks has in common i.e. climate impact, other impact categories in the PEF and EPD are not necessary for the comparison. A summary of the impact assessment (IA) method and the characterization factors according to different frameworks is shown in Table 1.

Table 1. Choices of impact categories and impact assessment models applied in this thesis

Framework	**IA method**	**CFs of common GHGs**		
		CO_2	**CH_4**	**N_2O**
PEF	IPCC 2013	1	28.5 for biogenic CH_4, 29.7 for fossil CH_4	264.8
EPD	CML 2001 Baseline (version August, 2016)	1	28.5 for biogenic CH_4, 29.7 for fossil CH_4	264.8
REDII	GHGs with specified characterization factors (CFs)	1	25	298

3.9 Summary of the general frameworks

A summary of the three frameworks in general regarding their application, modelling and calculation methods is shown in Table 2.

Table 2. Summary of PEF, EPD and REDII framework for environmental assessment of HVO from UCO

Description	**PEF**	**EPD**	**REDII**
Purposes	A harmonized methods approach to measure and communicate the environmental impact of products, services or companies.	Communicate environmental information in a way that enables comparison between products with the same function.	EU's regulation, report GHG emissions of transportation fuel, which needs to comply with the reduction target.
Intended audience	Business to business and business to consumer.	Mainly business to business and sometime business-to-consumer.	Authorities
Structure of frameworks	Similar to ISO-standard.	Similar to ISO-standard.	Accounting formula of GHG emissions through life cycle's perspective.
Scope			
Functional unit	Not specified in the general instructions but expected to be specifically given in the product categories' PEFCR.	Not specified in the GPI but expected to be specifically given in the product categories' PCR.	1 MJ
System boundaries	Cradle-to-grave	Cradle-to-grave	Cradle-to-grave
Type of LCA	Combined ALCA and CLCA	ALCA	Mainly ALCA
Cut-off	Usually not allowed, but 1% cut-off criterion can be applied.	The maximum cut-off criterion is 1 %.	Not allowed, all emission must be included according to the formula.
Capital goods	Should be included according to the guidelines but has been debatable. A new suggestion from JRC says that capital goods shall be excluded (EC, 2019).	Specified in the product categories' PCR.	Excluded
Allocation			
Multifuntional process	Decision hierarchy i) subdivision or system expansion ii) allocation based on physical relationship iii) allocation based on other relationship.	i) Subdivision ii) allocation based on physical relationship iii) allocation based on other relationship. Further specifications shall be specified in the PCR.	Allocation based on energy content. For cogeneration of electricity and heat, the allocation shall be based on the temperature of the heat.
Recycling, reuse and recovery	Circular Footprint Formula (CFF)	Polluter Pays Principle (PPP) approach	Waste and residues shall be considered to have zero GHG emission up to the collection of the waste.
Environmental impact assessment			
Default impact categories	16 default EF impact categories	7 default impact categories	Climate impact - GHG emissions (g CO_2 eq)
Assessment of climate impact	Account for uptakes and emissions from fossil, biogenic and direct land use change.	Account for uptakes and emissions from fossil, biogenic and direct land use change.	Account for GHG emissions from fossil and land use change.

4. Case study

This section describes the practice of the three frameworks to the case study of HVO from UCO. Here it can be seen that the frameworks' different interpretations of key principles, such as the allocation approach for the use of secondary material, affects the delineation of the system boundaries. The functional unit is determined and the frameworks' choice of allocation method for multifunctional processes in the case study are specified. The accounting of biogenic CO_2, capital goods and system cut-off are stated. Furthermore, details over the collection and quality of the data used for the case study are provided.

The UCO studied was collected in Sweden and assumed to consist of 50% palm oil and 50% rapeseed oil. The oil palm was assumed to be cultivated and processed in Indonesia or Malaysia. The rapeseeds are assumed to be cultivated in Germany and processed into rapeseed oil in Europe. Germany and Europe were chosen because of the data availability, which is applicable in this case study since Germany is the largest producer of rapeseed within Europe (Biofuels International, 2021). In addition, the case study compared the environmental impact when HVO was produced from UCO collected in Sweden and UCO collected in China in order to identify the most environmentally preferred alternative. The upstream processes of the palm oil were assumed to be the same for both cases. For the rapeseed oil, the upstream processes differ from the Swedish case as it was assumed that the rapeseed oil used in China was produced within the country. The production of the HVO occurred at Preem's refinery in Gothenburg, where the UCO was used as a feedstock.

4.1 Choice of functional unit

The functional unit that was used for all three frameworks is 1 MJ of energy out from the combustion of HVO fuel in a diesel engine of a heavy-duty truck (EURO V). 1 MJ was chosen as it is a common functional unit for biofuels. The other specifications required by the PEF and EPD frameworks were omitted in this as it is not relevant for the calculation and comparison.

4.2 System boundary and allocation of secondary material

The use of UCO is considered as a recycling of waste into another product i.e. HVO. This would affect the system boundaries for the different frameworks as different allocation methods were applied. The PEF framework applies CFF. In this case, no virgin material is used as a feedstock in the HVO production ($R_1 = 1$), and the energy recovery and waste management of the fuel are not relevant. This leads to that only Equation 2 and 3 are relevant. The CFF can therefore be reduced into:

$$(\boldsymbol{R_1}\times\boldsymbol{E_{rec}})-\left((\boldsymbol{1}-\boldsymbol{A})\boldsymbol{R_1}\times(\boldsymbol{E_{rec}}-\boldsymbol{E_V}\times\frac{Q_{sin}}{Q_P})\right) \qquad \text{(Equation 9)}$$

Where

R_1 = the proportion of the input of recycled material;
E_{rec} = specific emissions and resources consumed per functional unit resulting from the recycling; of the waste including collection, sorting and transportation;
A = allocation factor of burdens and credited between supplier and user of recycled materials;
E_V = specific emissions and resources consumed per functional unit resulting from acquisition and pre-processing of the virgin materials
Q_{sin} = quality of the ingoing secondary material, at the point of substitution
Q_p = quality of the primary material.

The A value is not given specifically for UCO but for used olive oil it is given as 0.5. Hence, it is reasonable that the A factor should be chosen as 0.5. The number indicates the equilibrium between supply and demand. The ratio between Q_{sin} and Q_p is the quality between the HVO and the cooking oil. In this case, a wholesale price of HVO and cooking oil (palm and rapeseed oil) is used as a proxy for quality.

At the time of the study, the global wholesale price of the palm oil and rapeseed oil was 967 USD/ton and 1220 USD/ton respectively (International Monetary Fund, 2021a; International Monetary Fund, 2021b). The wholesale price of the HVO was assumed to be the same as the price for Fatty Acid Methyl Ester (FAME), which was 1490 USD/ton (Biodiesel prices (SME & FAME), 2021). Since the price of the HVO is higher than the price of the cooking oil, the quality ratio Q_{sin}/Q_p was set to 1.

After applying the value to all of the parameters, Equation 9 can be simplified into Equation 10.

$$CFF = 0.5E_v + 0.5E_{rec} \qquad \text{(Equation 10)}$$

Equation 10 shows that half of the emissions from the upstream of UCO (cultivation and production of virgin cooking oil) is allocated to the HVO production. This means that the system boundary in the PEF framework was a cradle-to-grave.

The EPD framework applies the PPP approach. The point where the UCO has its lowest market value is when it is discarded to the waste collector. Thus, the system boundary would start after the UCO collection process. This means that in this study, a cut-off was applied in the EPD's system boundary, and the system started at the pretreatment of UCO and ended in the combustion of the HVO fuel.

For the REDII framework UCO is classified as a waste, which means that the environmental impact from the upstream processes of UCO was not counted in the calculations. Hence, a cut-off was applied in the REDII system boundary. The REDII's system boundary starts at collection of UCO and ends at distribution of the HVO. As the system boundary of the life cycle of the HVO for REDII is cut-off, some parameters in Equation 7 can be eliminated including e_{ec}, e_l, e_{sca} and e_u. The e_u was excluded because the emission from fuel in use for biofules is considered as zero. The HVO production has no carbon saving from CO_2 capture. Thus, e_{ccs} and e_{ccr} value can also be excluded. This gives a final equation for the calculation of the GHG emissions in this case study. See Equation 11.

$$E = e_p + e_{td} \qquad \text{(Equation 11)}$$

To remind, e_p is the emissions from processing of the HVO and e_{td} is the emissions from transportation and distribution.

Figure 1 shows an overview and comparison over the system boundary between the three frameworks.

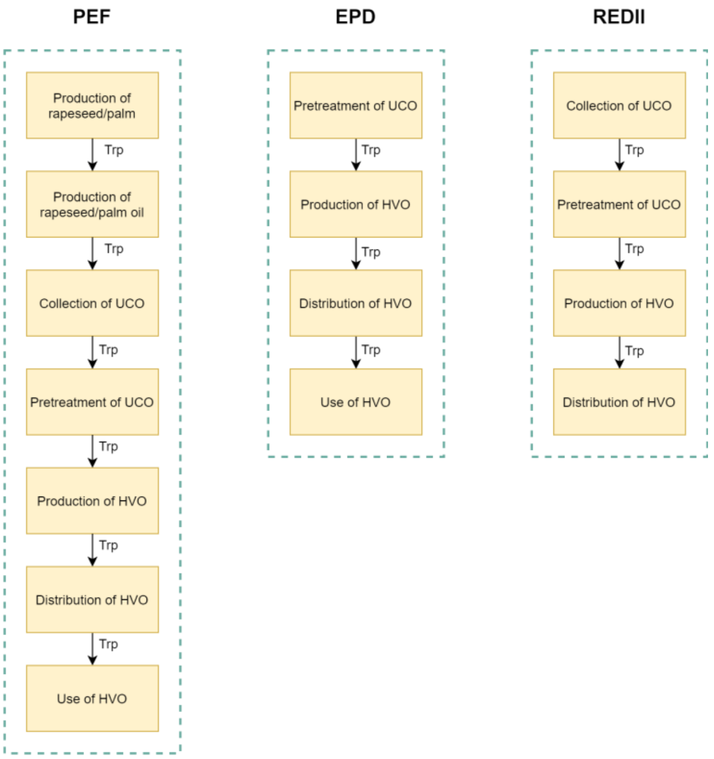

Figure 1. System boundaries applied in this study according to PEF, EPD and REDII framework

4.3 Allocation: multifunctional processes

The upstream processes of UCO produce multiple outputs, which leads to allocation problems. For the crude palm oil production, Crude Palm Oil (CPO) and kernels are produced. The kernels are considered a co-product since they can be used to produce kernel oil and animal fodder. An allocation based on mass is chosen to partition the environmental impact between the two products. The allocation factors used for the CPO and the kernels are 0.8 and 0.2 respectively. Palm oil production also produces biomass residues. The residues go back to the field and stay within the system. Thus, no allocation is needed. The same applies for residues that are used for energy recovery. The refinery of palm oil produces Refined Palm Oil (RPO) and Palm Fatty Acid Distillate (PFAD) as co-product. The mass allocation factors used for the RPO and the PFAD are 0.96 and 0.044 respectively.

The production of rapeseed oil (RSO) produces rapeseed meal as co-product. A mass allocation is used to allocate the environmental impact of the rapeseed oil and rapeseed meal. The allocation factors used for the RSO and the rapeseed meal produced in Europe are 0.40 and 0.60 respectively. For the RSO and rapeseed meal produced in China, the mass allocation used are 0.26 and 0.74 respectively.

Another allocation problem can be found in the HVO production. The process produces HVO, methane, propane and excess of steam. The methane and propane can be recirculated to the process as fuel gas. Hence, only the allocation between the HVO and steam needs to be done. Substitution was chosen as an alternative to allocation for the PEF and REDII model. Despite the statement that substitution is only allowed for policy analysis in REDII, the method seems to be accepted for use in the calculations under certain circumstances. The excess steam is used in other processes in the production plant as a substitute for steam that otherwise would be produced in a boiler fueled by natural gas. The saving of natural gas leads to a reduction in CO_2 emission by 10.2 kg CO_2 per ton UCO (K. Persson, personal communication, April 8, 2021). For the EPD model, the allocation was done based on the lower heating value of the HVO and the steam.

Figure 2 shows the processes where allocation needs to be applied.

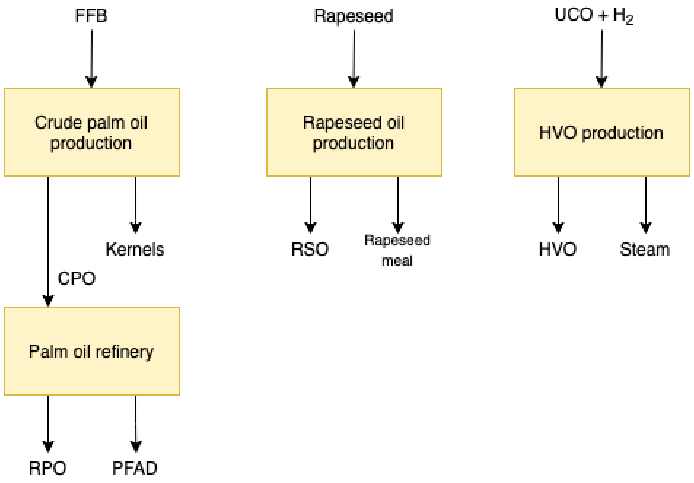

Figure 2. Allocation problems identified in the life cycle of HVO from UCO

4.4 Impact assessment modelling and presentation

Climate change was chosen as impact category as it is the only impact that are relevant for comparison between the three frameworks. For the PEF model, the uptake and emissions of biogenic CO_2 is more or less circular through photosynthesis and combustion. Hence, the biogenic CO_2 was not included in the PEF's calculations. For the EPD model, the carbon stored in the UCO was the same as the carbon stored in the cooking oil according to the EPD framework. However, the stored carbon can be considered to off-set all the emissions from the UCO processing, HVO production and the combustion of the HVO. Hence, biogenic CO_2 was not accounted for. For the REDII model, the biogenic CO_2 emissions was not included since UCO is biobased.

The result of the climate change impact according to the EPD framework was reported separately by the source of the carbon emissions. However, for the PEF result, the calculation of the impact from separate source of carbon emissions was not possible with the available software. This is due to the fact that the PEF result involves the use of CFF which means that the result obtained from OpenLCA cannot be used directly to report the environmental impact for each sub-category.

4.5 System cut-off

In this study, packaging for the vegetable oil and the isomerization step during the HVO production are assumed to be cut-off. An isomerization step is done in order to improve the properties of the HVO to meet Swedish's winter-standard. The isomerization step was assumed to be cut-off because it only consumes a small amount of electricity, steam and fuel gas in relation to the HVO process (K. Persson, personal communication, February 23, 2021). In addition, the isomerization is complicated and can vary depending on what type of catalyst is used. In this study it is therefore assumed that the isomerization step has an environmental impact less than 1% of the total without calculating beforehand.

The same assumption is applied for the packaging of vegetable oil. The cut-off of the isomerization step was applied to all three models. The cut-off of the production of the packaging of the vegetable oil is only relevant in the upstream processes of the UCO. Thus, it was applied only to the PEF model.

4.6 Capital goods

For the EPD, it would state in a PCR whether capital goods are to be considered in the calculation or not. Since there is no PCR for biofuels, the inclusion or exclusion of the capital goods cannot be said for certain. However, based on the PCR 2020:05 Basic products from forestry version 1.0, in the PCR it is stated that the manufacturing of production equipment, buildings and other capital goods shall not be included in the model. It is therefore reasonable to assume that capital goods shall not be included in the EPD model. Since the relevancy of the capital goods in the PEF is debatable, they were chosen to be excluded from the PEF calculations in this study. Another reason for this decision is that the data for the capital goods in each process can be unavailable or difficult to find.

For the REDII, there is no mention for the use of capital goods in the calculation. Thus, the capital goods are also excluded in the model. In short, the study excludes the environmental impacts of capital goods in all three of the frameworks.

Despite requirements in the three frameworks to ensure the data quality, a data quality assessment was excluded in this study, since it is not relevant to the comparison of the frameworks. However, the data used in the study were chosen based on the representativeness with regards to technology, geography and time relevance as far as the data were available. As it is not possible to apply specific data on all of the processes generic and average data are used instead.

4.7 Data collection and data quality

Regarding the calculation and assessment of the HVO from UCO, the type of data used were determined by the requirement in each framework. In general, primary data in cooperation with Preem were collected whenever possible. Generic data and average data were used in case that specific data could not be accessed or was unavailable. Generic data was obtained from scientific literature, databases and published company reports.

Background processes such as the upstream processes of UCO, the pretreatment process of the UCO and the H_2 production were modelled using generic life cycle inventory data from literature study. The inventory data for the production of products/inputs used in each process such as electricity, chemicals and fertilizers are obtained from Ecoinvent. The study was modelled in the software program OpenLCA (version 1.10.2). The Ecoinvent database was also used to obtain missing background data needed for the assessment. Microsoft Excel was used to facilitate the collection of data and to do some calculation before the data was used as input in OpenLCA.

The inventory data for the palm fruit production was published in 2020 and represents the average data for Indonesia and Malaysia over the assuming rotation time of 25 years. The data for the palm oil production was from 2007-2020. For China's rapeseed production, the yield was obtained from FAOSTAT between 2019-2017. The rest of the inventory data has a range of period between 1983-2012. The time boundary for Europe’s rapeseed production is between 2000-2020, in which the yield was taken for the years 2001-2005. The rapeseed oil production in China and Europe has a time boundary of 2003 and between 1996-2003 respectively. The data for the hydrogen production was from 2008. The data was obtained from the European Commission’s standard values for emissions factors. A specific and present data for the HVO production was provided by Preem.

In this study, the only foreground process is the production of HVO, while the rest of the processes, including the production of hydrogen, are background systems.

To account for the emission associated with direct land use change, calculations according to PAS2050-1:2012 have been performed. To obtain data over expanding and contracting cropland due to land use change, data over the crop production for all crops in Germany, Malaysia, Indonesia and China were collected for the years 1999-2001 and the years 2016-2018. Data over forest land, land under permanent crops and land under permanent meadows and pastures was collected for each country during the same time period. The data was obtained from FAOSTAT.

After the calculations of direct land use change it was concluded that rapeseed from China does not cause land change while rapeseed from Germany and Palm oil from Indonesia and Malaysia does.

The use of electricity, fertilizers, pesticides, chemicals and other similar input materials are modeled with a provider. Thus, the upstream processes of the production of these materials are included. For electricity the provider is specific for the country, for the other input materials global value or market value are chosen. The provider is taken from the Ecoinvent database.

4.8 Assumptions and limitations

One limitation in this case study is related to the modelling of electricity, where the energy mix for specific countries was applied. The data was obtained from Ecoinvent database. However, the dataset does not provide which year the energy mix represent. If the data over a country's energy mix is out of date the energy mix may have changed and the data will not represent the current situation.

Another limitation is related to the nature of the used software. OpenLCA does not support the CFF, which make it difficult to provide data required in the PEF framework such as reporting of climate impact separately for each sub-category (biogenic and LULUC).

Several assumptions are made in this case study. Assumptions related to the calculations are:

- Hydrogen is produced by natural gas through steam reformation
- Rapeseed oil is produced by solvent extraction.
- Palm Oil Mill Effluent (POME) and Empty Fruit Bunches (EFB) which are applied to the field do not have fertilizer effect to the oil palm. Hence, no substitution of artificial fertilizers is considered.
- When modelling, unspecified pesticides are used.
- Electricity mix of the country is up to date.
- Cut-offs are applied in case of lack of data such as drying process and storage of rapeseed.
- The isomerization step and the container of cooking oil have less than 1% contribution to the total impact and cut-offs are applied.
- Co-products such as methane and propane are assumed to only be used as fuel gas within the HVO process.
- The collection of UCO in Sweden is done by Svensk Fettåtervinning.

4.9 Sensitivity analysis

The sensitivity of the results was tested by changing the mixing ratio of UCO in the HVO process. The type and proportion of different UCO determine the amount of H_2 that is needed in the process. As a result, it would also affect the yield of HVO, methane and propane. In this study, UCO from 100% palm oil (PO) and UCO from 100% rapeseed oil (RSO) were modelled in the sensitivity analysis. The case of mixed UCO was used as a base line.

Table 3 shows the summary of the framework and calculation methods that were applied specifically to the case study.

Table 3. summary of the framework and calculation methods that were applied specifically to the case study

Description	**PEF**	**EPD**	**REDII**
Scope			
Functional unit	1 MJ	1 MJ	1 MJ
System boundaries	Cradle-to-grave	Pretreatment of UCO to the combustion of the HVO.	From the collection of the UCO to the distribution of the HVO.
Cut-off	Packaging for the cooking oil and the isomerization step.	Upstream processes of the UCO, packaging for the cooking oil, the collection of the UCO and the isomerization step.	Upstream processes of the UCO, packaging for the cooking oil and the isomerization step
Capital goods	Excluded according to suggestion from JRC (EC, 2019)	Excluded	Excluded
Allocation			
Co-products	Allocation based on mass for the co-products in the cooking oil production. Substitution for steam.	Allocation based on lower heating value for steam.	Substitution for steam.
Recycling of secondary material	CFF approach	PPP approach	Waste and residues shall be considered to have zero GHG emission up to the collection of the waste.
Environmental impact assessment			
Impact categories	Only climate change will be assessed.	Only climate change will be assessed.	Only climate change will be assessed.
Assessment of climate impact	Uptake and emissions of biogenic CO_2 is excluded due to circular flow.	Uptake and emissions of biogenic CO_2 is excluded due to circular flow.	Biogenic CO_2 is not accounted for

5. Inventory data analysis

This section describes the processes needed to produce HVO from UCO. These processes include production of oil crops such as rapeseed and oil palm, and their conversion to refined oil suitable for the food industry. Furthermore, details about the steps involved in the collection of the UCO, the pretreatment of the UCO, the hydrogen production and the HVO production are described. For all processes, details regarding the inputs and outputs for all environmentally relevant flows are listed. A flowchart over the life cycle of the HVO from a mixture of used rapeseed oil and used palm oil according to the PEF, EPD and REDII is shown in Figure 3 for the purpose of a visual representation of the system. Transportation is excluded in the flowchart.

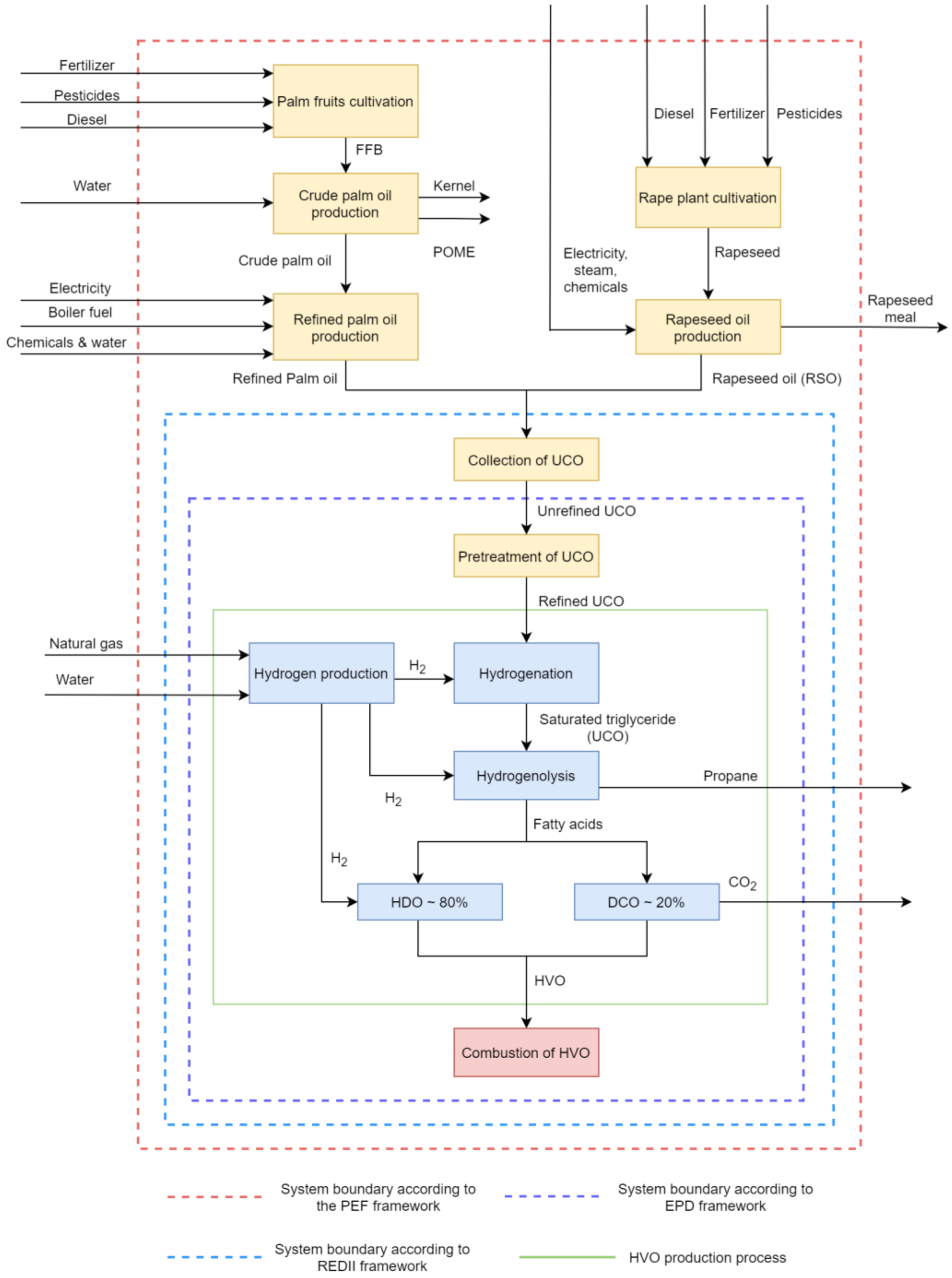

Figure 3. A flowchart over the whole life cycle of HVO fuel from mixed UCO (50% palm oil and 50% rapeseed oil)

5.1 Rapeseed production

China and Europe are among the world's largest rape and rapeseed oil producers (Shahbandeh, 2021b). This means that the origin of rapeseed oil in UCO will differ since the rapeseed oil collected in Sweden would most likely be produced in Europe and the one collected in China would most likely be produced within the country. It can occur that the rapeseed oil consumed in China are imported. However, this aspect will not be taken in consideration in this study.

Rape plants are annual crops which can be planted on clay or sandy soil. There are two types of rapeseeds that can be planted at different times of the year: winter rapeseed and spring rapeseed. In this study, both types are considered. Chen and Chen (2010) provide data on the input of the production of rapeseed in China, which covers agricultural stages such as ploughing, mulch tillage, seed drilling, rolling and harvesting. The plantation requires application of fertilizers, herbicides and pesticides as well as the use of diesel to drive machines. The yield of Chinese rapeseed is obtained from FAOSTAT database. An average yield from 2017 to 2019 is calculated to 2025 kg/ha. Since specific types of herbicides, insecticides and fungicides are not known, the amount of these compounds was summed as unspecified pesticides with an amount of 0.57 g/kg rapeseed when modelled in OpenLCA. China's electricity mix was chosen.

A calculation according to PAS 2050-1:2012 (BSI, 2012) shows that there is no emission from land use change for the cultivation of rapeseed (RS) in China. The emission of the phosphate in China RS was calculated by using the calculation suggested in Schmidt (2007), which suggest that the leaching of phosphate is 2.9% of the P surplus. See the calculation in Appendix C, part 1.

The data on the rapeseed production in China is summarized in Table 4.

Table 4. Data for rapeseed production in China (Chen & Chen, 2010; Schmidt, 2007; PEFCR guidance v.6.3 (EC, 2018))

Description	Quantity	Unit
Input		
Diesel	14.9	kg/ha
N-fertilizer	180.00	kg/ha
P-fertilizer	67.50	kg/ha
K2O-fertilizer	34.50	kg/ha
Herbicide	0.10	kg/ha
Fungicide	1.00	kg/ha
Insecticide	0.05	kg/ha
Electricity	500.00	MJ/ha
Output		
Yield of rapeseed	2025.07	kg/ha
Ammonia (NH_3) to air	21.86	kg/ha
Nitrous oxide (N_2O) to air	3.96	Kg/ha
Nitrate (NO_3^-) to water	239.14	Kg/ha
Phosphate (PO_4^{3-}) to water	0.49	kg/ha

In case of Swedish UCO, the rapeseed was assumed to be produce in Germany. The inventory data was obtained from the Ecoinvent database (Jungbluth et al., 2007) where RS was produced with conventional production method. The database includes the use of machines and diesel consumption for agricultural steps such as fertilizing, ploughing, harrowing, sowing, application of plant protection, harvesting and chiseling. The yield of the RS used in the database is 3413 kg/ha, which is an average yield from FAOSTAT during the period between 2001 and 2005.

After the harvesting process, the rapeseeds are to be dried and stored. However, the data for this was not available in China's case. Hence, for the sake of comparison, the drying process was excluded from the modelling in both cases.

The CO_2 emission from land use change was calculated according to PAS 2050-1:2012 (BSI, 2012) and the calculation is shown in Appendix C, part 2. The data used for Europe's rapeseed production is shown in Table 5.

Table 5. Data for rapeseed production in Germany (Jungbluth et al., 2007)

Description	**Quantity**	**Unit**
Input		
Diesel	3088.44	MJ/ha
N-fertilizer	238.90	kg/ha
P_2O_5-fertilizer	128.00	kg/ha
K_2O-fertilizer	284.30	kg/ha
Herbicide	0.77	kg/ha
Fungicide	0.13	kg/ha
Insecticide	0.09	kg/ha
Seed	3.50	kg/ha
Output		
Rapeseed	3413.00	kg/ha
Ammonia (NH_3) to air	28.67	kg/ha
Nitrous oxide (N_2O) to air	5.26	kg/ha
Nitrogen oxides (NO_X)to air	3.57E-05	kg/kg RS
Phosphorus to surface water	1.19E-05	kg/kg RS
Phosphorus to ground water	2.05E-06	kg/kg RS
Nitrate (NO_3^-) to ground water	317.74	kg/ha
CO_2 from direct land use change	681.17	kg/ha

The harvesting of rapeseed produces straws as a co-product or residue. The straws can be regarded as co-product if it is used as energy source and it can be regarded as crop residue if they are left on the field (Nikander, 2008). In this study, the rape straw is regarded as residue and was not included in the calculation as it did not leave the system.

The emissions of ammonia (NH_3), nitrous oxide (N_2O) and nitrate (NO_3^-) in both Sweden and China case was calculated by using the emission factors given by the PEFCR guidance v.6.3 (EC, 2018). The emission factors for the NH_3, N_2O and NO_3^- are 0.12 kg NH_3 /kg N fertilizer applied, 0.022 kg N_2O/ kg N fertilizer applied and 1.33 kg NO_3^- /kg N applied, respectively. In addition, in China's case, specific compounds of herbicides, fungicides and insecticides were unknown. Thus, for both cases, the amount of the herbicides, fungicides and insecticides were summed up as unspecified pesticides in both cases in the modelling.

Flowcharts of the rapeseed production in China and Germany are shown in Figure 4 and Figure 5 respectively.

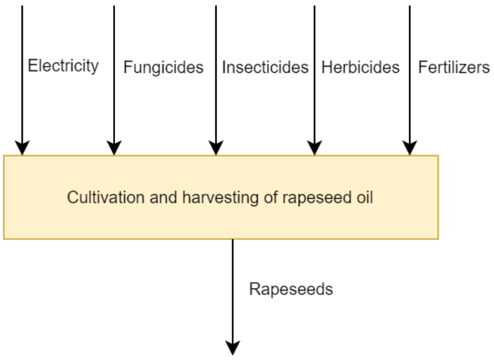

Figure 4. Flowchart of rapeseed production in China

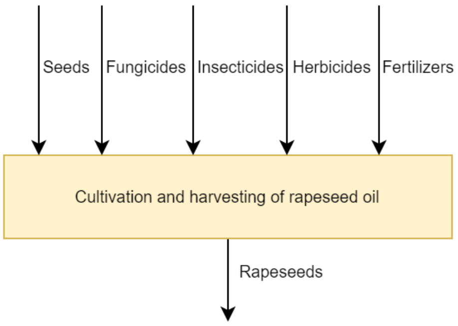

Figure 5. Flowchart of rapeseed production in Germany

5.2 Rapeseed oil production

Rapeseed oil (RSO) can be produced mainly by two methods: full pressing and solvent extraction (Nikander, 2008). In this study, the extraction method is chosen since it gives a higher purity and a higher efficiency (Jungbluth et al., 2007). In this study, the extraction method is used in both Europe and China.

The data for the RSO production in China was obtained from Li et al. (2014). The extraction of RSO is divided into three processes: seed preparation, mechanical extraction and solvent extraction. The preparation step includes cleaning of seeds, pre-heating, crushing and cooking (direct steaming). During the mechanical extraction, the RS is pressed and produces oil and press cakes. The press cakes are extracted further in the solvent extraction step where hexane is used as a solvent. The mixture of oil and solvent is then separated by distillation. The process also produces rapeseed meal as a co-product. (Li et al., 2014). The used hexane solvent is recirculating in the process.

The oil content of rapeseed is approximately 40-45% according to Li et al. (2014). The pressing step gives about 60% of the oil. While the oil yield during the solvent extraction process is 58.2%. Li et al. did not provide data on the energy consumption. Hence, data from Schmidt (2007) was used for the heat and electricity consumption in process instead. The inventory for China's RSO production is shown in Table 6. China's electricity mix was chosen, and transportation mode was assumed to be lorry (16-32 t, unregulated class) where diesel is used as fuel.

Table 6. Data for rapeseed oil production in China (Li et al., 2014; Schmidt, 2007)

Description	**Quanitity**	**Unit**
Input		
Rapeseed (RS)	1.00	kg
Electricity	0.42	MJ/kg RSO
Heat (steam)	1.59	MJ/kg RSO
Transportation (farm to mill)	100.00	km
Output		
Rapeseed oil (RSO)	0.26	kg/kg RS
Rapeseed meal	0.72	kg/kg RS
Losses	0.02	kg/kg RS

In Europe, the data for RSO was obtained from the Ecoinvent database (Jungbluth et al., 2007) where rapeseed oil was produced in Europe (without Switzerland). The extraction process for Europe provided in Jungbluth et al. (2007) is similar to the one described in the Chinese case. The transportation of RS from the farm to the oil mil is an average distance of 100 km by a 16t lorry. Table 7 shows the data for the production of RSO in Europe. Europe's energy mix was chosen as the source of electricity and the transportation mean was assumed to be by lorry (16-32 t, Euro V) where diesel is used as fuel.

Table 7. Data for rapeseed oil production in Europe

Description	**Quantity**	**Unit**
Input		
Rapeseed (RS)	1.00	ton
Phosphoric acid	0.300	kg/ ton RS
Activated bentonite	2.30	kg/ ton RS
Hexane	1.10	kg/ ton RS
Electricity	151.20	MJ/t RSO
Heat (steam) from gas combustion	707.70	MJ/ t RSO
Output		
Rapeseed oil	395.60	kg/t RS
Rapeseed meal	604.40	kg/t RS
Effluent (Waste Water)	2.70	kg/t RS
Hexane to air	1.10	kg/t RS

The production of RSO in both cases has an allocation problem since more than one product was produced. The allocation problem for China case was solved by using a mass allocation factor of 0.26 for RSO and 0.74 for rapeseed meal, while for Sweden a mass allocation factor of 0.4 and 0.6 were used for RSO and rapeseed meal respectively. Flowcharts of the RSO production in China and Europe are shown in Figure 6 and Figure 7 respectively.

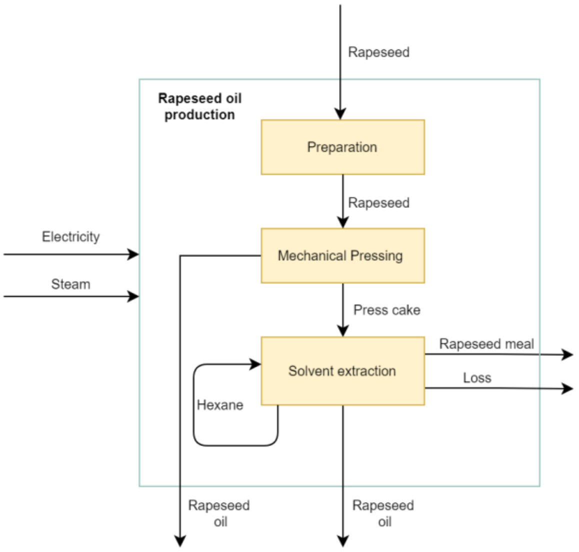

Figure 6. Flowchart of rapeseed oil production in China

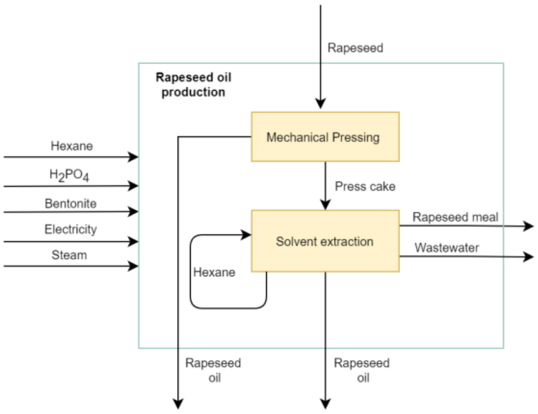

Figure 7.Flowchart of rapeseed oil production in Europe

5.3 Palm fruit production

Palm oil (PO) is a highly saturated eatable vegetable oil that comes from the oil palm species *Elaeis guineensis*. The oil palm only grows close to the equator where the warm and humid climate gives optimal growing conditions. With a yield between 4-10 times higher than for other vegetable oils (WWF, 2020) the oil has become widespread because its low cost and the demand for the oil is increasing. The global production of vegetable oil of the market year 2020/2021 amounted to 209.14 metric tons, of these, palm oil's share accounted for 75.45 metric tons (Shahbandeh, 2021c). One of the main concerns associated with PO is the loss of tropical forest and peatlands that has been converted to monoculture oil palm plantages (Voora et al., 2020).

Indonesia and Malaysia are the largest of the worlds PO producers and stand for around 90 % of the worlds market (WWF, n.d.) while China is the second largest importer of palm oil (Workman, 2021). In this study average data over the total palm oil cultivation in Indonesia and Malaysia is used. The data over the cultivation step is obtained from Schmidt and De Rosa (2020). The data over the production of fertilizers, pesticides and herbicides is obtained from the Ecoinvent database. See Table 8.

The oil palm is a perennial crop. During the first year the oil palm seeds are cultivated in a nursery before being planted into the field. The field has been treated with pesticides and a legume cover crop are sown to protect the soil and to help fixate nitrogen. Around each palm plant a circle is left to not add any competitive vegetation to the palm, this is called a palm circle. Herbicides are applied inside the circle to keep the oil palm free from weeds (Schmidt, 2007). After two years of growth in the field, the palm trees are mature enough for their fruit to be harvest. The fruit grows in bunches, every bunch weighting around 25 kg (Schmidt, 2007). Every 10 days the bunches are ready to be harvested. The harvesting is done manually with a knife attached to a pole. To enable a fast growth, nutrients in form of fertilizers and crop residues are applied (Socfin, n.d.).

The average rotation time is around 25-30 years, after this time the palm trees have become 10 meter high and are too high to harvest manually. The fresh fruit bunches (FFB) consist of 20% oil, 5% kernels, 13%fiber 7%shell and 23% empty fruit bunches (EFB). The FFB are transported by truck to the oil palm mill with a distance assumed to be 17 km (Nikander, 2008). In truck was assumed to be a diesel-engine lorry, 16-32 t, unregulated class.

Some assumptions for the production of PO are made. The preparing of the land, palm seeds and sowed cover crops were not taken into consideration. Several different pesticides and herbicides are used but will be aggregated into the total amount.

The emissions of ammonia (NH_3), nitrous oxide (N_2O) and nitrate (NO_3^-) was calculated by using the emission factors given by the PEFCR guidance v.6.3 (EC, 2018). The emission factors for the NH_3, N_2O and NO_3^- are 0.12 kg NH_3 /kg N fertilizer applied, 0.022 kg N_2O/ kg N fertilizer applied and 1.33 kg NO_3^- /kg N applied, respectively. The CO_2 emission from land use change was calculated according to PAS 2050-1:2012 (BSI, 2012) and the calculation is shown in Appendix C, part 2.

Table 8. Data for oil palm production (Schmidt and De Rosa, 2020; Schmidt, 2007; Stichnothe and Schuchardt, 2011)

Description	Quantity	Unit
Input		
Fuel use	2940.00	MJ/ha
Applied mineral N	82.00	kg N/ha
Applied mineral P_2O5	41.00	kg P2O5/ha
Applied mineral K_2O	156.00	kg K2O/ha
Pestesides[1]	9.50	kg/ha
Output		
FFB	18900.00	kg/ha
Nitrate (NO_3^-) to water	109.06	kg/ha
Ammonia (NH_3) to air	9.84	kg/ha
Nitrous oxide (N_2O) to air	1.80	kg /ha
Phosphorus to water[2]	1.60	kg/ha
Nitric oxide (NO) to air[2]	3.20	kg/ha
CO_2 emissions from land transformation	13453.07	kg/ha

[1] Stichnothe and Schuchardt, (2011), [2] Schmidt, (2007), Schmidt and De Rosa (2020).

5.4 Palm oil production

At the oil palm mill the FFB are first treated with steam to be sterilized. Thereafter the bunches go to rotating drums that helps stripping the fruits from the bunches (Socfin, n.d.). The residues of the stripped bunches, that is the EFB, are returned to the field and act as organic fertiliser (Plantations International, n.d.). The next step is digestion, where the fruits are treated mechanically and thermally to help release the oil from the cells inside the fruits. The fruits are thereafter pressed mechanically, and the crude oil mixed with water, fiber and other solids are extracted from the fruit pulp. The mixture is then purified by boiling, thereafter centrifuged and dried.

From the centrifuge step wastewater called Palm Oil Mill Effluent (POME) is removed and brought back to be applied as an organic fertilizer to the fields. From the pressing step, fibers and the nut of the palm oil fruit called kernel are separated. From the kernel, palm kernel oil can be extracted leaving a palm kernel press cake, which can be used as animal fodder. This often occur in a separated process outside the palm oil mill and thus is outside the scope of this study. The fibers and the kernel shells are recovered for energy in a boiler that will generate enough steam and electricity to power the oil palm mill, meaning that the oil palm mill is energy self-sufficient (Nikander, 2008). The crude palm oil (CPO) must be refined before it can be used for cooking. The refinery process removes impurities like gums, waxes, trace metals, free fatty acid and removes bad smells and discoloring (Schmidt, 2007). The refinery generates food-graded Refined Palm Oil (RPO) and Palm Fatty Acid Destillate (PFAD). PFAD is a residue that can be utilized further in biofuel production, as animal feed or as an ingredient in other oleochemical products. As the processes produce multiple outputs allocation problems occur both between the CPO and the kernels in the palm oil mill and between RPO and PFAD in the refinery step. An allocation based on mass is chosen to partition the environmental impact between the products. The allocation factors used for the CPO and the kernels are 0.8 and 0.2 respectively. The mass allocation factors used for the RPO and the PFAD are 0.96 and 0.044 respectively. The production of CPO is showed in Figure 8. The data over the crude and refined palm oil production is showed in Table 9 and in Table 10.

Some assumptions are made for the production of PO. POME and EFB which are applied to the field are assumed to have no fertilizer effect to the oil palm. Hence, no substitution of artificial fertilizers will be calculated. For the energy recovery, it is assumed to only supply energy consumption in the palm oil mill and that there is no excess energy to supply electricity outside the system. As stated in Schmidt and De Rosa (2020) only 5% of all POME is treated for biogas capture which can be considered negligible. Thus, in this study, it is assumed that no biogas is captured. The electricity in the refinery process was assumed to be Indonesia's energy mix from Ecoinvent.

Table 9. Data for palm oil production, input and output (Schmidt and De Rosa (2020); Schmidt (2007); Warman et al., (2019); Stichnothe and Schuchardt (2011))

Description	**Quantity**	**Unit**
Input		
FFB[1]	18900.00	kg/ha
Water[2]	12285.00	kg/ha
Electricity (incineration of biomass)[3]	1178,71	MJ/ha
Output		
Crude Palm oil (CPO)[2]	3780.00	kg/ha
Kernel[2]	945.00	kg/ha
Carbon monoxide (CO)[2]	19.25	kg/ha
Methane (CH_4)[4]	141.75	kg/ha
Nitric Oxide (NO)[2]	12.62	kg/ha
Nitrogen oxides (NO_2)[2]	0.06	kg/ha
Sulfur dioxide (SO_2)[2]	0.06	kg/ha

[1] Schmidt and De Rosa (2020), [2] Schmidt (2007), [3] Warman et al., (2019) [4]Stichnothe and Schuchardt (2011).

Table 10. Data for refinery of palm oil (Tan et al., 2010)

Description	**Quantity**	**Unit**
Input		
Electricity from grid	11.94	kWh
Boiler fuel fossil	476.91	MJ
Water	113.39	litre
Crude Palm Oil (CPO)	1050.00	kg
Phosphoric acid	0.59	kg
Bleaching earth (activated bentonite)	9.11	kg
Output		
Refined Palm Oil (RPO)	1000.00	kg
Waste water	42.16	litre
Palm fatty acid distillate (PFAD)	45.62	kg
Spent bleaching earth (activated bentonite)	11.09	kg
Wastewater biochemical oxygen demand (BOD)	1.12	kg
Wastewater chemical oxygen demand (COD)	3.26	kg

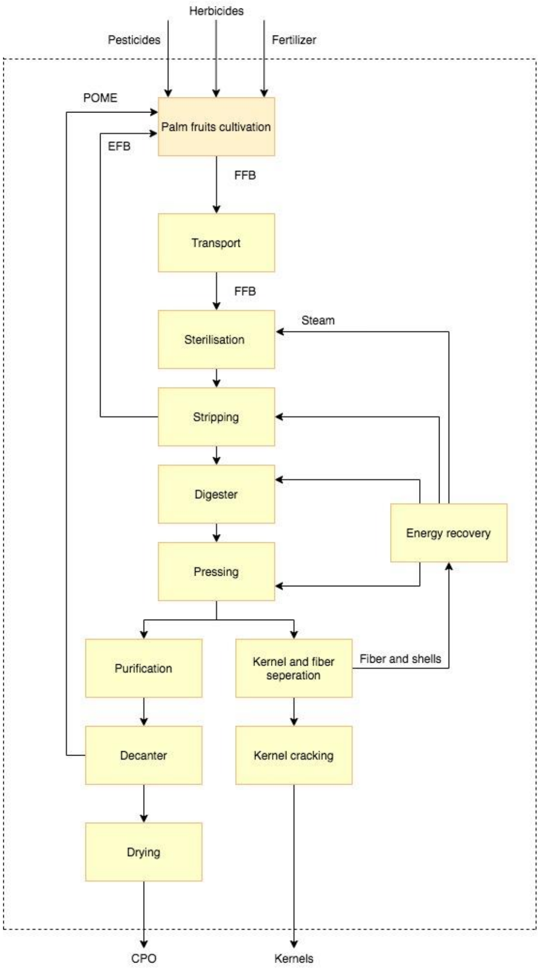

Figure 8: Flowchart over the palm oil production process

5.5 Collection of UCO

In Sweden and China, a decentralized collection system is used (Svensk Fettåtervinning, n.d.a; Behrends, 2018). The system means that collectors pick up UCO door-to-door at different facilities such as restaurants, catering facilities and stores. The UCO from households was not considered in this study.

In Sweden, Svensk Fettåtervinning is assumed to be the UCO collector. The company has a refinery for pre-treatment of UCO in Norrköping (Svensk Fettåtervinning, n.d.b). The company collects the UCO by trucks within Götaland and Svealand region (up to Östersund) (Svensk Fettåtervinning, n.d.c). 50% of the company’s customers is in Stockholm region (Svensk Fettåtervinning, n.d.a). Thus, it is assumed that the company travel mostly within the Stockholm region (Norrköping - Stockholm). A calculation of the average distance of the UCO collection is shown in Table 8. Since the UCO is more likely to be collected in Stockholm than in Östersund and Ystad, a double distance to Stockholm was applied to lower the mean distance. The average distance of the UCO collection in Sweden was calculated to be 374 km. The UCO was transported back directly to the refinery. Hence, no storage was considered. See Table 11 for the collection distance.

Table 11. Data for collection distance of UCO in Sweden

Origin	Destination	Distance (km)	Transportation mode	Fuel
Östersund	Norrköping	714.00	Truck	Diesel
Ystad	Norrköping	456.00	Truck	Diesel
Stockholm	Norrköping	163.00	Truck	Diesel
Stockholm	Norrköping	163.00	Truck	Diesel
Mean distance	374.00 km			

According to Behrends (2018), the collection of UCO in China occurs within a radius of 35 km. The collected UCO is pretreated in a processing plant before it is shipped to ARA-area.

5.6 Pretreatment of UCO

For the UCO to be used as feedstock for HVO production, it needs to be treated beforehand. This is in order to remove impurities such as suspended impurities, rubber soluble impurities (e.g. phospholipids and proteins), fat-soluble impurities (e.g. Free Fatty Acid (FFA)) and traces of metals (Chen, 2016; Lorenzi et al., 2018). These contaminants in the UCO can affect the quality of the HVO and stability if they are not treated properly.

The pretreatment of UCO mainly consists of three steps: degumming, neutralization and bleaching (Lorenzi et al., 2018). The degumming process is done by adding water and then centrifuged to separate impurities such as phospholipids, proteins and gums, that are insoluble in oil when hydrated. The neutralization step is needed in order to reduce acidity of the UCO by using alkaline solutions such as sodium hydroxide (NaOH) (Nikander, 2008). The last step is bleaching, which decolorizes the oil by removing traces of metals, non-converted phospholipids and other contaminants (Lorenzi et al., 2018).

In this study, it was assumed that the pretreatment process of UCO looks the same in China and in Sweden. However, a country- or region-specific data on electricity mix is used in order to differentiate the two processes. The inventory data for the pretreatment process was provided by Nikander (2008) and partly by Behrends (2018) where the amount of sodium hydroxide (NaOH) and phosphoric acid (H_3PO_4) were obtained. See Table 12. The flowchart of the pretreatment process is shown in Figure 9.

Table 12. Data for pretreatment process of UCO (Nikander, 2008; Behrends, 2018)

Data	Quantity	Unit
Input		
UCO	1214.00	kg
H_3PO_4	1,15	kg
NaOH	1,85	kg
Cooling water	70.00	kg
Process water	28.00	kg
Steam	657.00	MJ
Electricity	50.00	MJ
Output		
Pretreated UCO	1191.00	kg
Waste water	111.00	kg

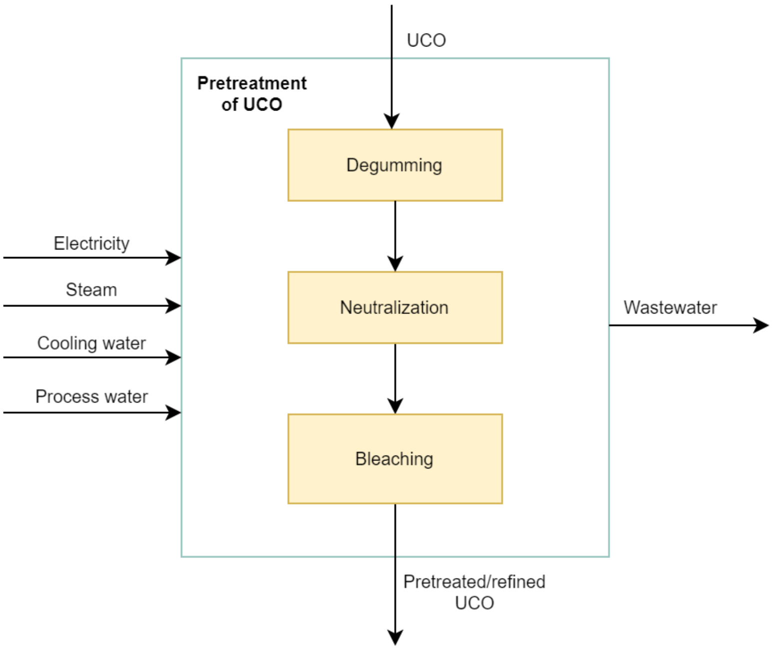

Figure 9. Flowchart of pretreatment process of UCO

5.7 Transportation of UCO to the HVO production plant

The pretreated UCO from China is transported to the ARA-area by ship. The port of Shanghai is assumed to be the port where the UCO is being shipped because it is the busiest port in China (Schwerdtfeger, 2020). Firstly, the UCO is transported from different part of the country to the port. One of the requirements that Preem has on their UCO supply chain is that it must be certified with the International Sustainability & Carbon Certification (ISCC). In China, there are four regions where the biggest and most of the ISCC-certified UCO collectors are located: Jiangsu, Hebei, Guangdong and Sichuan (Chen, 2019; Poon, 2019).

Thus, an average distance from the four regions to the port of Shanghai is chosen as the transport distance. However, Jiangsu is located approximately 92.5 km from Shanghai, which is a relatively short distance compared to other regions. Thus, the distance from Jiangsu to Shanghai is excluded in the calculation since it brings down the average distance significantly. As a result, the average distance of the UCO to the port is estimated to be 1690 km. In this study, it is assumed that the UCO is transported by train powered by fossil fuel.

The UCO is then transported to the port of Rotterdam (ARA-area) and later to the port of Gothenburg. The transportation from the port of Gothenburg to Preem’s HVO production plant is assumed to be negligible. A summary of the data related the transportation of UCO to the production plant is shown in Table 13.

Table 13. Data for transportation of UCO from China to Preem’s HVO production plant in Sweden

Origin	**Destination**	**Distance (km)**	**Transportation mode**	**Fuel type**
China	Port of Shanghai	1690.00	Train	Fossil fuel
Port of Shanghai	Port of Rotterdam	22222.00	Ship	HFO
Port of Rotterdam	Port of Gothenburg	1122.00	Ship	HFO

As mentioned in section 5.5 the collected UCO in Sweden is being treated in a refinery in Norrköping. It is assumed that the UCO is sent to Preem's HVO production plant in Gothenburg by truck with a distance of 312 km.

5.8 Hydrogen production

Hydrogen can be produced through several methods for example through catalytic reformation, steam reformation or electrolysis (K. Persson, personal communication, February 25, 2021). In this study, it was assumed that the hydrogen is produced at Preem's refinery through steam reformation, where fossil natural gas is used as a feedstock. The natural gas is assumed to have a methane content of 95.06 molar percent, which was the average for 2020 (Swedgas, 2020). The data for the emissions from the hydrogen process was taken from European Commission's standard values for emission factors of hydrogen for HVO production (EC, 2020).

The process starts with the methane reacts with water and form hydrogen and carbon monoxide, see Reaction 1. This reaction requires a metal-based catalyst and a temperature of 700-1100°C. The carbon monoxide will thereafter react further with water and form additional hydrogen and carbon dioxide, see Reaction 2 (My Fuel Cell, 2021).

Stoichiometrically, this would mean that for each CH_4 molecule, four H_2 molecules are formed. In addition, the produced hydrogen's weight would be around 50 percent of the weight of the CH_4 input (K. Persson, personal communication, February 25, 2021). Table 14 shows the data for the production of hydrogen.

$$CH_4 + H_2O \rightleftharpoons CO + 3\,H_2 \qquad \text{(Reaction 1)}$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \qquad \text{(Reaction 2)}$$

Table 14. Data for hydrogen production (EC, 2020)

Description	**Quantity**	**Unit**
Input		
Natural gas (NG)	1.00	kg
H_2O	2.00	kg/kg NG
Output		
H_2	0.45	kg/kg NG
CO_2	80.87	gCO_2/MJ H_2
CH_4	0.28	gCH_4/MJ H_2
N_2O	3.00E-03	gN_2O/MJ H_2

5.9 HVO production

HVO biodiesel is produced through a two-stage hydroprocessing process where the triglycerides in the UCO is treated with H_2 (see Figure 10). In the first stage, hydrotreatment or hydrogenation, H_2 is used to saturate the double bonds in the triglycerides into single bonds. The reaction occurs under high temperatures at 300-390°C. When all the double bonds have been saturated additionally H_2 is added which will convert the triglycerides into propane (C_3H_8) and linear fatty acids.

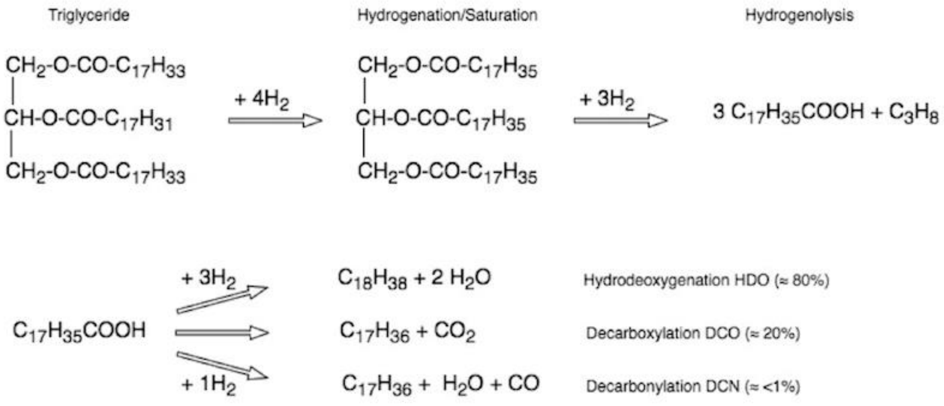

Figure 10: The reactions show how rape seed oil are converted into HVO fuel

To form the HVO, the oxygen present in the fatty acids needs to be removed (ETIP Bioenergy, n.d.). The process is called hydrogenolysis. This can be done by three different pathways: hydrodeoxygeneration (HDO), decarboxylation (DCO) or by decarbonylation (DCN). The DCN is a combination of HDO and DCO and is not used as much in the process as the other two (less than 1%).

Thus, in this study, only HDO and DCO are considered as the reaction pathways. 70-90% of the process can be done through HDO and 10-30% can be done through DCO. In this study, it was assumed that 80% of the HVO is produced through HDO and 20% through DCO. The difference between the HDO and the DCO is the presence of H_2. In the HDO pathway H_2 is added. The H_2 reacts with the O_2 and form water. In the DCO pathway hydrogen is not required and the O_2 will be released as CO_2. During the hydroprocessing, the fuel gases CH_4 and C_3H_8 are formed. The fuel gas produced is enough to generate the energy needed to fuel the entire HVO process and the excess fuel gas (propane) can be sold on the market (K. Persson, personal communication, February 25, 2021). However, in this case study, it was assumed that all fuel gas and propane were used internally for the HVO production. For the electricity, the Swedish energy mix was used. The inventory data for the HVO production from a mixture of 50% rapeseed and 50% palm oil are shown in Table 15.

Table 15. Inventory data of the production of HVO from 50% used RSO and 50% used PO

Description	**Quantity**	**Unit**
Input		
Used RSO	0.500	ton
Used PO	0.500	ton
H_2	0.03	ton
Electricity	14.00	kWh/ ton UCO
Fuel gas (from by-products)	270.00	MJ/ ton UCO
Output		
HVO	0.85	ton
C_3H_8	0.05	ton
CH_4	3.00E-03	ton
H_2O	0.11	ton
Steam (net production)	0.06	ton/ ton UCO

During the HVO process a net production of steam is formed as a co-product. This causes an allocation problem, which was handled in two different ways depending on which framework was applied. Substitution was applied in the case where the PEF and REDII framework was used. For the EPD model, allocation based on energy value was used. Currently, Preem uses the excess steam to substitute heat used in another process, which would otherwise be produced from natural gas. The saving of natural gas has lowered the fossil CO_2 emission by 10.2 kg CO_2/ ton UCO (K. Persson, personal communication, April 8, 2021).

In case of allocation based on energy, LHV was chosen as a basis. The LHV of the HVO is 44.1MJ/kg (Neste, 2014) and the LHV for the produced steam is 2.74 MJ/kg (K. Persson, personal communication, April 9, 2021). The allocation factors for the HVO and the steam were calculated to be 0.94 and 0.006 respectively.

After the HVO is formed, the next step is to improve the cold flow properties of the HVO so the fuel can operate in a cold climate. This step is required in Sweden and other Nordic countries. The hydrocarbons undergo a cracking and/ or isomerization step, branching the hydrocarbons. The produced HVO biodiesel are a sulfur and aromatic free (ETIP Bioenergy, n.d.). However, in this study, it was assumed that this step has less than 1% environmental impact and so the process can be cut-off. The flowchart of the production of HVO is showed in Figure 11.

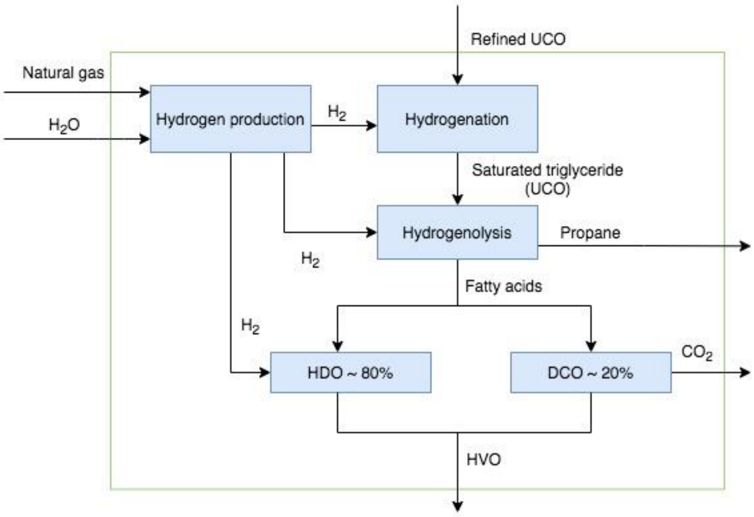

Figure 11: Flowchart over the HVO process

5.10 Transportation and distribution of HVO

After the HVO is produced, it is transported by ship to Preem’s depots in Sweden and Norway. The depots are located in five cities in Sweden and one city in Norway: Helsingborg, Karlshamn, Gävle, Norrköpping, Stockholm (Loudden), Piteå and Sandefjord (Norway). An average distance between the six depots is obtained. When the HVO reaches the depots, it is then transported by trucks to smaller stations. It was assumed that the HVO is distributed within the radius of 50 km by a Euro V lorry>32 metric ton with diesel as fuel. The shipping container of the HVO was assumed to be a tanker for petroleum. The inventory data is shown in Table 16.

Table 16. Data for transportation and distribution of HVO

Origin	**Destination**	**Distance (km)**	**Transportation mode**	**Fuel type**
Gothenburg	Depots	521.00	Ship	HFO
Depots	Preem’s gas stations	50.00	Truck	Diesel

5.11 Combustion of HVO

In this study, the HVO is assumed to be used by a heavy-duty truck (Euro V) in Sweden. The lower heat value of HVO is 44.1 MJ/kg (Neste, 2014). The data on the emissions from the combustion is obtained from the CPM-LCA database (Swedish Life Cycle Center) provided by f3 centre (Hallberg et al., 2013). See Table 17. The emission of CO_2 is not included in the data because it considered as non-fossil.

Table 17. Data for combustion of 1 MJ HVO (Hallberg et al., 2013)

Description	**Quantity**	**Unit**
Input		
HVO	1.00	MJ
Ouput (to air)		
CO	4.90E-04	kg
CH4	6.72E-06	kg
Nitrogen oxides,NOx	2.44E-04	kg
Nitrous oxides, N_2O	6.11E-06	kg
NMVOC	6.05E-05	kg
PM	3.67E-06	kg
Sulfur dioxide, SO2	1.36E-07	kg

6. Results

This section presents the environmental impact from the modelling of PEF, EPD and REDII when applied on the case study HVO from UCO. The environmental impacts from different processes will be presented in a contribution analysis. In addition, the result from comparing the environmental impact of HVO when using Swedish UCO and Chinese UCO is shown. The sensitivity of the results from the case study will be tested by changing the mixing ratio of the UCO and an uncertainty analysis is presented.

6.1 Environmental impact results of PEF, EPD and REDII model

The climate change impact of HVO from a mixture of 50% Swedish UCO from PO and 50% Swedish UCO from RSO is shown in Figure 12. The climate impact for the PEF and EPD should be presented as kg CO_2-eq. However, to make the illustrations of the results easier to comprehend, the unit of the climate impact shown in the diagram is done according to the unit required in the REDII (g CO_2-eq).

As seen in Figure 12, the result calculated with the PEF framework has the highest impact (51.3 g CO_2-eq/MJ), follow by EPD (14.7 g CO_2-eq/MJ) and REDII (11.9 g CO_2-eq/MJ). Comparing to the PEF result, the climate impact in the EPD and REDII model are lowered by 71% and 77% respectively. The significant decrease in the environmental impacts shows that it does matter which environmental framework is used to assess the environmental performance of a product.

The emissions saving of the HVO, which is calculated according to REDII framework is 87% when compared to the fossil comparator for biofuels (94 g CO_2-eq/MJ). The difference in the impact mainly depends on that the three frameworks have different system boundaries. Therefore, the default cradle-to-grave system boundary is not always true. When a material is recycled e.g. the recycling of UCO into HVO, different frameworks have different rules for how this allocation problem should be handled. The PPP used in the EPD and REDII's interpretation use of waste have led to a cut-off in the system boundary, while the PEF still account for UCO's upstream processes by using the CFF. This also means the emissions from land use change during cultivation is not always included in the EPD and REDII.

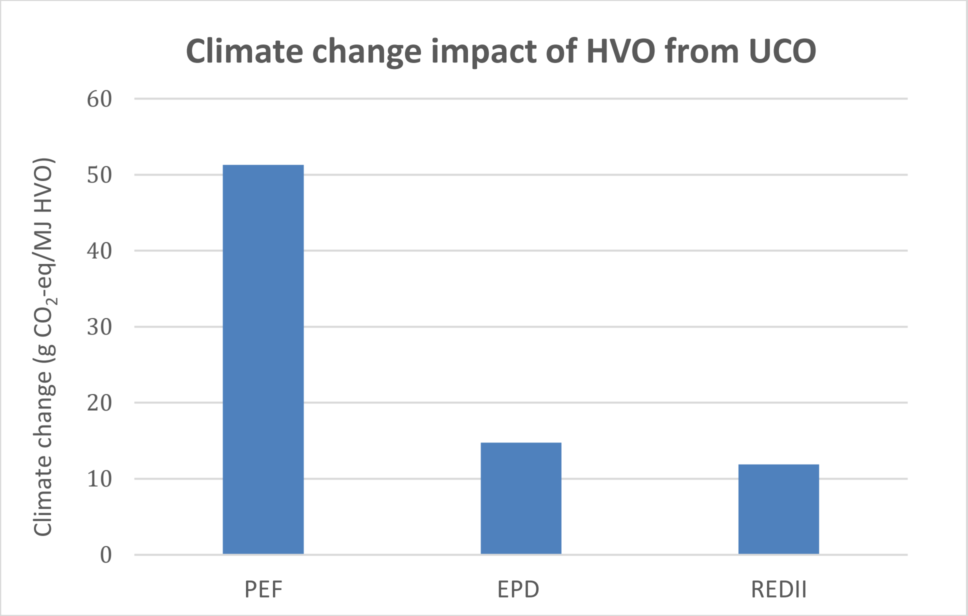

Figure 12. Climate impact of using 1 MJ HVO in a heavy-duty truck (EURO V) according to PEF, EPD and REDII framework.

For our case study the PEF framework gives the highest impact as it is the only framework that includes the upstream processes of the UCO in the system. The circular footprint formula allocates part of this impact to the virgin cooking oil, which is not included in our system. In our case, the formula shows the impact of the production of HVO with the simplified circular footprint formula $0.5E_{rec} + 0.5E_v$. This means that half of the impact from the upstream processes of the UCO and half of the impact from the recycling process were allocated to the HVO production.

In the EPD framework, the PPP approach allocates the whole impact of UCO's upstream processes to the polluter, that is, the user of the virgin cooking oil, and this part of the system becomes cut-off. By not including the upstream of UCO the EPD framework has a 70% less impact compared to the impact in the PEF framework. As UCO as a feedstock is a waste, the REDII framework cut-off the system and not include the UCO's upstream processes, making the REDII system have 77% less impact compared to the PEF framework.

Even if the PEF framework takes the whole life cycle into account, depending on the magnitude of the impact from the upstream processes of UCO, the CFF could lead to a lower overall impact compared to the EPD and the REDII frameworks even if this is not the case in our case study.

The REDII framework gives the lowest impact of all the frameworks as it only takes three GHGs into account while the PEF and the EPD framework account for many more, which leads to a higher GWP. The different frameworks also have different CFs for some of the GHGs, meaning that the same GHGs are accounted for differently in the different frameworks. The CFs used in the PEF and EPD framework is essentially the same, while the CFs used in the REDII differ. The CF for N_2O in REDII is 298 which is 13% higher than the CF used in PEF and EPD (264.8). The REDII's CF for CH_4 on the other hand is 25, which is 14% lower than those used in the two frameworks (between 29-30). When using the REDII CFs in the PEF model, the PEF's result decreased by 0.3%. The decrease in climate impact result implies that CH_4 contributes to the total impact more than the N_2O and that the differences in the CF for the CH_4 is dominating the differences in the CF of the N_2O in this case. However, since the change in the CFs leads to insignificant change in the testing model, the result seen in Figure 12 is likely not affected by the fact that different frameworks have different CFs.

Another difference between the three frameworks is the accounting of the biogenic carbon (CO_2, CH_4 and CO). The PEF and EPD framework states that the uptakes (removals) and emissions from biogenic source should be accounted for, while the REDII explicitly disregard biogenic uptakes and emissions. Despite this specification in the PEF and EPD framework, it was chosen that the biogenic CO_2 uptakes and emissions from the use of UCO can be excluded from the calculation since the uptakes of the CO_2 should balance the emissions in the product's life cycle. Hence, all the three frameworks may not necessarily consider the biogenic CO_2 into the calculation. Another difference is that the REDII framework completely overlook the emissions from the use (combustion) of biofuels. This makes the downstream processes in the system boundary look different when the three frameworks were applied.

6.2 Report of EPD's result

The EPD's framework required that the GWP100 result shall be reported separately by the source of the carbon GHG emissions, which are fossil, biogenic and LULUC. Figure 13 shows the reporting of the GWP of the EPD's model from different sources.

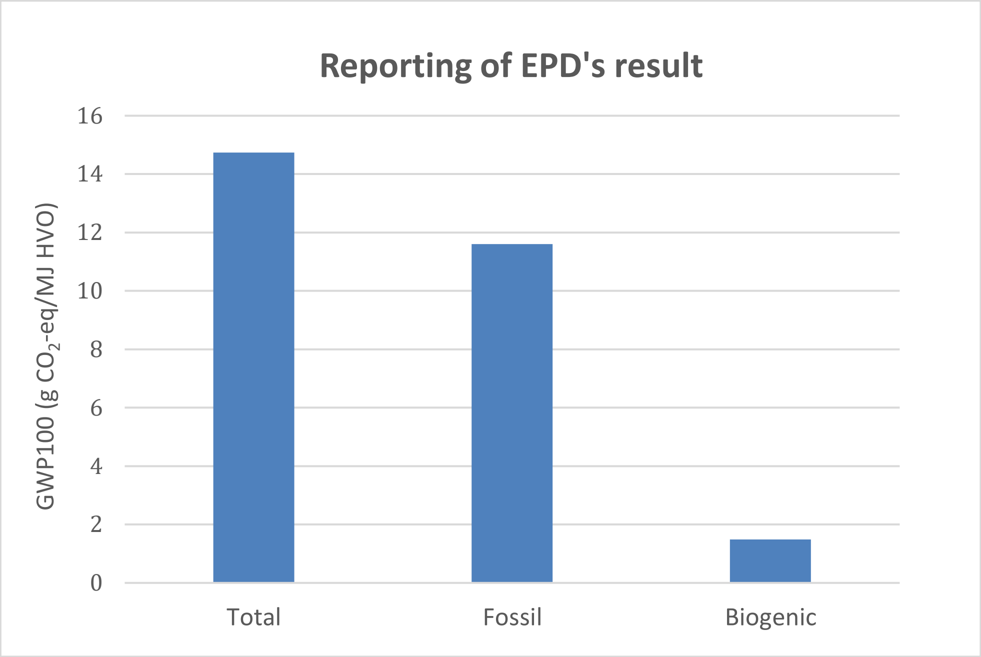

Figure 13. Reporting of EPD's result (GWP100) from different sources of carbon emissions

Figure 13 shows that the GWP, fossil is 0.012 kg CO2-eq which correspond to 80% of the total impact. The GWP, biogenic is 0.0015 kg CO2-eq, which stands for 10% of the total impact. This means that the majority of the GHG emissions arise from fossil origin. The rest 10% of the emissions come from other GHG emissions that are not carbon-based. The PEF also require that the biogenic and LULUC emissions to be reported separately if they contribute to more than 5% of the total impact during the screening process. However, this information could not be obtained in OpenLCA as it does not support the use of CFF. Hence, the reporting of the PEF study cannot be presented.

6.3 Contribution analysis

An analysis of contribution of different processes to the climate change impact of the HVO from mixed UCO according to different frameworks was carried out and the results is shown in Figure 14.

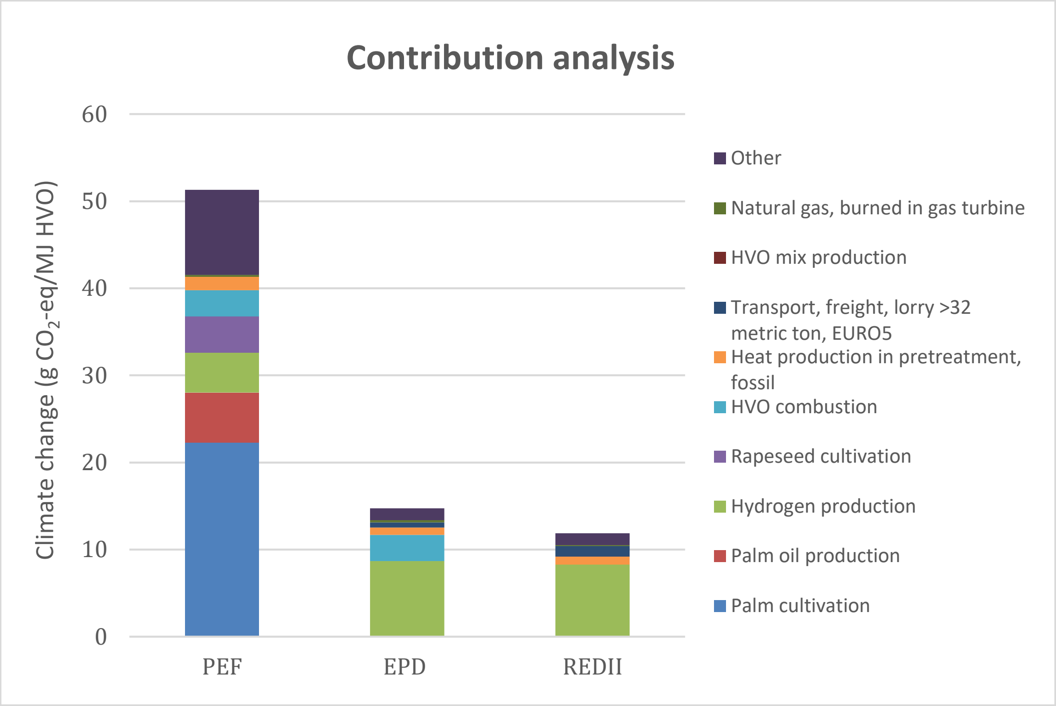

Figure 14. Contribution of processes in the life cycle of HVO from mixed UCO.

The result in Figure 14 shows that 55% of the environmental impact in the PEF comes from the upstream processes of palm oil, which are cultivation and palm oil production. This major contribution can be explained mainly from the substantial impact from Land Use Change (LUC) during cultivation of palm fruit, which implies that there has been a high rate of deforestation in the previous 20 years. An increase in the demand of UCO can potentially lead to more virgin oil (especially PO) is being produced in order to keep up with the UCO's demand. As a result, carbon emissions due to LUC can increase, which would increase the overall environmental impact in the PEF further.

The biggest hotspot for the EPD and the REDII is the hydrogen production, which contributes respectively to 60% and 70% of the total impact. The hydrogen is assumed to be produced through steam reformation which uses natural gas as a feedstock. Hence, the process is the main source of fossil GHG emissions in the EPD and the REDII system. The H_2 can be produced by using a renewable feedstock or by using biproducts from the HVO production, such as propane. This would decrease the environmental impact even further, especially in the EPD and the REDII.

However, in the PEF model, the hydrogen production contributes to only 9% of the total impact. This means that the upstream of the UCO is the most significant stage in the life cycle of the HVO. Furthermore, this emphasizes that the main difference in the three framework lies primarily on the different system boundary when secondary material is used, and other differences discussed in section 6.1 play minor roles.

6.4 Swedish UCO vs Chinese UCO

A comparison between two origins of the collection of UCO is shown in Figure 15. The UCO that is collected in China needs to be shipped to Sweden, which means that the transportation distance increases compared to when the UCO is collected locally. Another factor that differs between the

Swedish and Chinese UCO is the country where the rapeseed oil is produced. For the palm oil, the country of production is assumed to be the same.

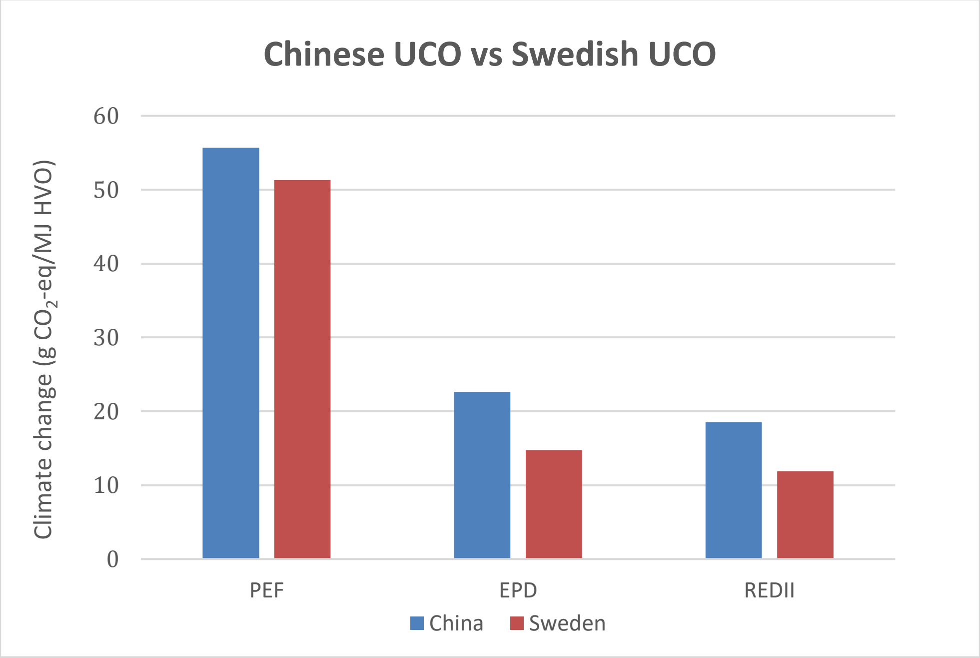

Figure 15. Climate impact of 1MJ HVO from UCO collected in Sweden and China, used by a heavy-duty truck (EURO V).

The result in Figure 15 shows that Chinese UCO has a higher impact than the Swedish UCO in all three frameworks. The use of Chinese UCO increases the impact by 8%, 32% and 36% in the case of PEF, EPD and REDII respectively. This can primarily be explained by the different transportation distances. The fact that Chinese rapeseed production does not cause land use change contrasts with the rapeseed production in Germany. However, this factor has less of a bearing on the results which means that Chinese UCO still produces a higher impact.

As a recommendation, Swedish UCO should be used if the production of the HVO is operated in Sweden.

6.5 Sensitivity analysis

The mixing ratio of the UCO is one of the input parameters that can affect the result. The proportion of the different types of the UCO that are used in the HVO production affect the upstream impact of the cooking oil as well as the consumption of H_2 in the hydrotreatment process. The amount of H_2 needed in the process depends on types of fatty acids in the UCO, which determine how many double bonds that need to be saturated with H_2. The mixing ratio of UCO is thus tested for its effect on the overall impact. In this case, the sensitivity analysis is done for mixed UCO (50% RSO and 50% PO), 100% rapeseed UCO and 100% palm UCO. The result is shown in Figure 16.

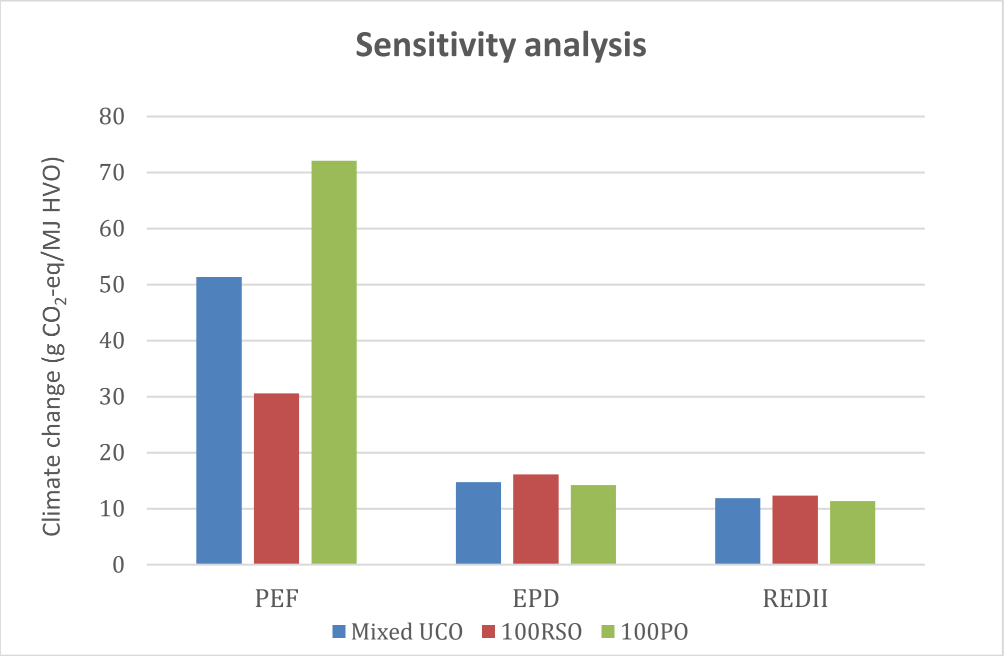

Figure 16. Sensitivity analysis of climate impact due to changes in mixing ratio of UCO

Figure 16 shows that the PEF is the most sensitive to the change in the mixing ratio of UCO. While for the EPD and the REDII, the parameter has no significant effect on the overall environmental impact. This implies that the type of UCO and how much each type of oil is used affect its upstream burden rather than the feed of H_2 needed to produce HVO. The PEF, which considers the upstream process, is therefore more sensitive to the change than the EPD and REDII.

The result in the PEF also shows that the palm UCO plays a greater role to the overall impact than the rapeseed UCO. One explanation is the higher land use change of PO, another that the production of PO requires heavier processing. However, if comparing the results between the EPD and REDII model, it can be noticed that 100PO gives lower impact than 100RSO. This can be explained by the fact that RSO has more double bonds than PO, which means that it needs more H_2 to saturate the double bonds into single bonds.

Another input parameter that can affect the results is crop yield of the material used as feedstock. Even if average data for the crop yields have been used for the calculations, the yields vary over the years which effect the cultivation stage. A lower yield would mean more input materials and higher emissions per kg product while the opposite would be true for a higher yield. This would affect the PEF result as a large part of the impact comes from the cultivation stage but not the EPD and REDII studies as this is outside the system.

6.6 Uncertainty analysis

There are some uncertainties around the data used in the calculation of the environmental impact of the HVO. This can affect the reliability of the results. Firstly, the data used in the calculation was mostly average data except for the HVO production. The use of average data can lead to that some values are overestimated and some are underestimated. Ideally, a more specific data would be preferred.

For the HVO production, the isomerization step was excluded from the system since the process was assumed to have less than 1% contribution to the total impact. This assumption should be tested beforehand in order to reduce the uncertainty of the result. In addition, modelling of electricity was made based on country that the process was assumed to occur. As the year of the electricity mix is missing in the database used in this study, it can occur that the data is not up to date. A specific electricity supplier may give different result.

In the case the upstream of the rapeseed in Sweden, the data was adapted from the Ecoinvent data. The data from Ecoinvent can be considered as reliable source but since some of the data was obtained from at least 20 years ago, it may be considered as outdated. In reality, the technology may have improved so that efficiency increases, more environmentally friendly equipment and chemicals are used, and less energy or electricity may be required. In addition, the choice of transportation mode and collection of the UCO was based on assumption, which may not reflect the real situation.

Furthermore, there were some unclear specifications in the framework for example choices of allocation methods, uptakes and emissions of biomass and the calculation of land use change. The ambiguity in the frameworks has been solved by consulting with an advisor who has experiences in the field of environmental system analysis frameworks. However, since the interpretation can vary, it can contribute to the uncertainty in the calculation. Hence, this would require a review and verification from an external party.

7. Analysis

This section analyses how the application of frameworks affect the environmental impact of the HVO from UCO. It brings up in detail how the frameworks handle co-products, the impact of LUC and the reliability of PAS2050. Additionally, limitations that have been identified during the study are presented.

7.1 Implication of frameworks in case study

The described differences in the accounting methodologies between the three frameworks in section 6.1 leads to different results when they were applied to the case study. The results show that the PEF model has the highest climate change impact, while the REDII model has the lowest impact.

The case study shows that the main methodological discrepancy between the three frameworks, which give rise to the different results, lies in the allocation approach when there is recycling, reuse or recovery of material and energy in the process. As it can be seen in the case study, the CFF and PPP was applied to the PEF and EPD model, while the REDII disregard the upstream of the waste completely. This leads to the fundamental difference in the system boundaries, which leads to the difference in the accounting of the impact in the life cycle of the HVO.

In addition, the analysis of the contribution of the HVO’s life cycle processes shows that the upstream of the UCO is the dominating process in the PEF model, while for the EPD and the REDII model, the H_2 production is the main contributor. When two origins of the UCO were compared, the results shows that the use of UCO collected in China increases the impact by 8%-36% depending on the applied framework. The result is primary due to that the UCO needs to be imported to the country producing the HVO, which leads to a longer transportation distance. As a result, the impact of the HVO using imported UCO increases significantly. It is therefore recommended for the HVO producer in Sweden to use UCO from Sweden if possible.

7.1.1 Handling of co-products

It is worth mentioning that the PEF makes a distinction between system expansion and substitution in its hierarchy, which is interesting since substitution is normally included as system expansion to avoid allocation problems. Apart from that system expansion and substitution are not allowed in EPD, the allocation hierarchy/rules for PEF and EPD are the same. The REDII does not have any rules or hierarchy but suggests that impact of co-products should be primarily partitioned and allocated based on energy content. Substitution can be used but only for policy analysis.

Therefore, it can be said that the main difference in how co-products is handled is the system expansion (including substitution). The PEF, which allows system expansion and substitution is more flexible but at the same time, it can become problematic if the framework is to be used to compare products that provide the same function. System expansion is less transparent and difficult to verify. Källmén et al. (2019) shows that when assessing HVO using system expansion, the GWP becomes lower than if partitioning is used. Hence, one may need to be careful when looking at the PEF result.

The EPD on the other hand, does not allow system expansion, which leads to results being easier to trace and have less variation. The REDII result can vary depending on which approach of handling co-products is used and what purpose of the assessment it is intended for. However, as the framework can be considered more toward ALCA and that allocation is based on only one physical relationship (energy content), the calculation method in general becomes less flexible and the result can be considered more transparent compared to the PEF.

7.1.2 Calculation of land use change

It is also worth mention that the use of PAS2050 to calculate the CO_2 emissions due to LULUC in the PEF model can be questioned as PAS2050 does not follow a cause-effect relationship. The method considers the change in carbon stock in soil and biomass of forest, grassland, perennial and annual crop over a period of 20 years. This means that PAS2050 uses a historical approach to LUC so the demand for PO and RSO is affected by historical LUC. Simplified, this can be interpreted as the effect of the demand for PO and RSO today caused deforestation and conversion of land 20 years ago. Intuitively, this would not make sense because what we do today should not affect things that has happened in the past.

In PEF, the environmental impact contribution from PO is much higher compared to RSO. This can be explained by differences in emissions from LUC. The average LUC from palm cultivation in Indonesia and Malaysia is almost 20 times higher than the LUC from RS cultivation in Germany. As the demand for PO is increasing, PO has act as a driver for deforestation of the tropical rainforest, the demand of RSO has not increased as fast as PO so the crop has not given rise to the same level of LUC.

Rapeseed cultivation in China does not cause LUC, a reason for this could be that RS in China is planted on already existing agriculture land. Another reason could be and that China during the last decades has been driving tree planting programs that could help balance out the conversion of land if RS cultivation caused any LUC (Rapid Transition Alliance, 2018).

Ideally, the calculation should account for the specific land use change the cooking oil, hence the UCO used in the HVO production have caused. However, the required data is not easily available, and it would require more resources to keep track of such activities, especially when the source of the UCO is not always transparent.

Other problems associated with the PAS2050 is how the instruction and its calculation examples are inconsistent with each other. The calculation of the land use change for perennial and annual crop is done differently in the calculation examples, but this is not mentioned anywhere in the instruction. Part of the calculation also relies on data on shares of forest area from 2000, which can be considered too old and can make the estimation of the land use change too aggressive. Hence, the number can be too high, which leads to an overestimation of the environmental impact of the product. There are several typos and errors in the text that lead to confusion and questions on its seriousness. In our opinion, the reliability and appropriateness of the PAS2050 is questionable.

7.2 Limitations

During the modelling and calculation processes, some limitations have been identified. The limitations include the problems with the interpretation of frameworks and limitations related to calculation methodologies, as discussed below.

7.2.1 Limitations related to calculation methodologies

For the PEF and EPD model, all the default impact categories have not been conducted since only the climate change impact can be compared between the three frameworks. Thus, a full environmental impact assessment for the PEF and EPD were not presented in the case study. In order to assessed more than one impact, more data and time would be needed. This implies that in practice, the PEF and EPD frameworks are more demanding and more comprehensive compared to the REDII.

Furthermore, due to different system boundaries, the amount of data required in each framework also differed. As PEF was the only framework that took the UCO's upstream processes into consideration, the time we spent on the PEF framework alone was more than for the other two frameworks. If a PEFCR and a PCR would have existed for biofuels it would have been easier to find and focus on the most relevant parameters for the study, saving both time and effort. To conduct an REDII study takes less time, and several excel tools for easier calculations are available if needed. This makes the REDII framework more user friendly and demands less knowledge than PEF and EPD.

In addition, as the software used in the project is not compatible with the PEF framework, the requirement on a separate reporting of the climate change impact by different sub-categories (biogenic and LULUC) could not be done. This complication comes from the fact that OpenLCA does not support the use of CFF in the modelling, which put the case study under some limitation. As it may require different rules for different product categories, it is not possible to create a general tool to be used for the PEF-calculation. Hence, there is no software we can use when this study was conducted.

7.2.2 Problems with interpretations of frameworks

When we tried to apply the three frameworks to our case study, some problems regarding the interpretation of methodologies in the frameworks were encountered. As some specification was not clear and can be interpreted differently, it may affect the reliability of our results.

7.2.2.1 The point at lowest market value

The PPP used in the EPD framework leads to a delineation of two product life cycles at the point where waste has its lowest market value. This delineation was not straightforward when we applied this to our case study. Fortunately, a diagram is provided in the GPI where it shows that point of separation for different cases of recycling, reuse and energy recovery. In our case where UCO is used to produce HVO, collection of waste should be excluded. This means that the UCO has the least value when it is collected by collectors. However, we think it can be argued that the waste should have a value if collectors decided to pick it up and that the point where UCO has the lowest value is when the consumers decided to discard the product after use.

This problem is being solved in the new version of the GPI (version 4.0), which was launched during the time this case study was carried out. The delineation between the two life cycles of products occurs instead at the point where waste is no longer waste. To determine the state of the waste, The GPI version 4.0 provides clearer criteria, which can be used to facilitate the definition of the scope of a study.

7.2.2.2 Choice of basis of allocation

When allocation problems cannot be avoided, the PEF and EPD states that allocation based on relevant underlying physical relationships or other relationships can be used. Normally, a PEFCR would specify more in detail for which physical or other relationships that can be considered, as well as which allocation values are to be used. However, since there is no PEFCR for biofuels, specification for which allocation basis to be prioritized is not available. In our study it was therefore interpreted that any physical property of input and output could be considered as acceptable as long as it is relevant to the function the co-products provide.

For the EPD, it shall be specified further in a PCR which specific physical relationships that should be considered. Again, as there is no PCR for biofuels, such specification was not provided and so it was interpreted as that the choice of allocation basis can be chosen freely. In our case study, a mass allocation was chosen to handle co-products in the RSO and PO production. However, some can argue that mass is not a suitable relationship for oil production as mass allocation would be more appropriate for food production such as products between cow meat and dairy. Some can say that it is questionable to use mass allocation as the market demand for the product of interest and the co-product are not equal. Hence, using mass allocation would result in an "unfair" partitioning. According to the GPI's allocation rules, this choice of allocation is however valid. If other physical relationships were to be used, then the result might look different.

7.2.2.3 Application of CFF

When reading about the CFF, it was not clear to us how it can be applied to our case study and what the result from the CFF would mean to our calculation. Fortunately, we were able to consult with an expert so the application of the CFF becomes easier to comprehend. Some terms used in the CFF are also difficult to understand. For example, the "point of substitution" which is mentioned in the definition of quality of material (Q-values). For Q_{sin}, it is defined as "*the quality of ingoing "recycled" material at point of substitution*". Here we have a problem understanding what recycled material is referred to in our case: the UCO or the HVO.

The point of substitution is referred to *"the point in the value chain where secondary materials substitute primary materials"* (EC, 2018). Here we would consider the secondary material would be UCO, and that primary material would be virgin cooking oil. Hence, the Q_{sin} should correspond to the quality of the UCO when it replaces the use of virgin cooking oil.

However, upon consulting this with the expert, the Q_{sin} can also be interpreted as the quality of the HVO since the point of substitution would be at the point of the value chain where the HVO replaces the conventional diesel i.e. at a gas station or when a consumer decides to use the HVO instead of fossil-based diesel. This shows that the interpretation for a parameter in the CFF is not straightforward. Since only some parts of the CFF are relevant in our study, other parts were not studied as much. Hence, it is possible that there can be a problem with interpretation for other parameters as well.

Furthermore, we found that we would have modelled the PEF model differently if we were to understand the use of CFF earlier. The presence of E_v and E_{rec} shows that we need to have those emissions separately and that the distribution and use stage of the HVO are not included in the equations but to be summed later with the result from the CFF. Thus, a whole life cycle of the HVO may not necessarily be modelled and calculated together. If we were to model the case study again, we would divide the life cycle stages and calculate the impact separately for each part.

7.2.2.4 Use of substitution for policy analysis

The REDII stated that substitution can be applied onto a calculation if it is used for the purpose of policy analysis. However, it does not specify any further what activities that can be considered as policy analysis. It was found that it can be acceptable to use substitution under certain circumstances other than policy analysis. Energy allocation can also be used but it was unclear for us how the excess steam should be classified as a co-product or a cogeneration of electricity and heat. As data for substitution was available, it was chosen as an alternative to allocation instead.

8. Discussion

This section compares the results and the findings from the case study with literature and discuss possible problems that may arise from the use of UCO.

8.1 Comparison of results to literature data

The results obtained from this case study can be compared to other literature values. A report from the f3 centre provides GWPs for different types of HVO from well-to-wheel (WTW) for example HVO from RSO and HVO from UCO (Källmén et al., 2019). The GWP for the HVO from RSO was calculated by using allocation based on economic value for feedstock production. It has a value of 58 g CO_2-eq. The GWP for the HVO from UCO, the GWP was found by applying a cut-off method and has a value of approximately 13 g CO_2-eq. The co-products in the HVO process were handled based on energy content in both cases.

The GWP for the HVO from RSO can be compared with the GWP in the PEF model since it considers the production of virgin cooking oil. The PEF model gives a GWP of 51 g CO_2-eq, which is the same magnitude as for the GWP of HVO from RSO. The moderately lower GWP in the PEF model is reasonable as it only accounts for half of upstream processes and that in our case study, upstream of PO was also considered.

The GWP for the HVO from UCO in the f3 report is comparable with the GWP calculated in the EPD model (15 g CO_2-eq.) as both applies a cut-off method. Both GWPs shows the same magnitude, where the GWP in the EPD model is slightly higher. However, the higher GWP in our EPD model is not reasonable as the system boundary in the f3 model includes the collection of waste, while our EPD model does not. As we consider less life cycle stages, we would expect the impact to be lower. The cut-off approach in the f3 report was done according to the condition for waste in the original Renewable Energy Directive (RED) framework. This mean that when waste is used, its life cycle emission is zero up to the point where waste is collected. However, since an exact detail of calculation cannot be compared, there can be other factors that make the GWP in the f3 report become slightly higher.

For the REDII model, its climate impact cannot be compared with the GWP provided in the f3 report. The REDII model excludes the use phase of the HVO, while this step is included in the f3 assessment. However, the REDII provides typical values of e_p and e_{td} for biofuel and bioliquid in Annex V part D. The typical values of e_p and e_{td} for HVO from "waste cooking oil" are 10.2 g CO_2-eq/MJ and 1.7 g CO_2-eq/MJ respectively. The sum of these two values is 11.9 g CO_2-eq/MJ which is essentially the same as the calculated value in our case.

8.2 Problems with UCO

As seen in our study, imported UCO from China causes a higher environmental impact compared to UCO from Sweden. This is due to the extra transport needed when the Chinese UCO is shipped to Sweden. As seen in EPD and REDII the upstream emission from using UCO accounts as zero. This leads to that the UCO becomes a more attractive feedstock for fuel producers and it creates a higher competition with the already existing use of UCO.

UCO in Asia has for a long time been used for animal feed. When the demand for UCO increases the UCO in the animal fodder has a risk of becoming replaced with cheap virgin cooking oil, like PO instead. This means that more virgin cooking oil must be produced, which in turn leads to more LUC and deforestation. Another risk with increasing demand of UCO is that it may lead to that UCO gets a higher price than virgin PO. This in turn increases the risk for fraud. When PO is cheaper than UCO, the UCO collectors may dilute the UCO with virgin PO which will increase the environmental impact, but this will go unnoticed in the calculations performed by the fuel producers and other stakeholders. Thus, it is important to have certification scheme like ISCC in place that follows up the origin of the UCO and make sure that the value chain is transparent and traceable.

Considering the problems that arise from the increasing use of UCO it is important that the frameworks have a way of handling these problems in an appropriate way. The PEF framework handles the problems that arise from the increasing use of UCO by the factor A in the CFF. The A factor is determined by the EC and indicate the market situation of secondary materials in relation to primary material. If the A factor has the value 0.2 the demand for the secondary material is high but the supply is low. This will result in a situation where the price of the secondary material is close to or the same as the price for primary material. If the A factor instead would have the value 0.5 the supply and the demand would be the same and the price for the secondary and primary material would be equal or unknown. When the A factor has been given a value of 0.8 the demand for the secondary material is low while the supply is high leading to that the market price for the secondary material is much lower than the price for virgin material (Wolf et al., 2019). Currently the list of A factors is very limited which may lead to that 0.5 is used as the A factor which in turn may not reflect the reality.

At present, the EPD and REDII framework disregards the problems arising from the increasing demand of UCO and do not have a way to handle these problems. In the original RED framework, similar problems have occurred before. Originally, PFAD was according to the definition in the RED framework classified as a waste, meaning that the emissions from PFAD should be count as zero. However, the benefit of using PFAD made the market value of PFAD rise to levels close to PO. To avoid the risk of PFAD to act as a driver for deforestation, the EC removed PFAD as a material that could be counted as zero from the RED framework (Transport & Environment, 2020). If the demand of UCO continues to increase, the EC may respond to this in the same way by removing UCO from the REDII so that the emissions from the upstream of UCO will no longer be counted as zero.

Comparing to PEF, The EPD and REDII framework may be considered extreme in the way that it is all or nothing. The framework either account for the whole environmental impact for the primary material or it assigns the waste material a zero value. It is therefore important that EPD and REDII have a way of handle the potential problems that arise when the frameworks encourage the use of waste. In our opinion, the secondary material should also bear some burden from the production of primary material so that it reflects the reality of how much each material contributes to the emissions.

8.3 Comparison of findings in case study and literature

Previous studies conducted by Del Borghi et al. (2019) and Durão et al. (2020) have compared methodologies in the PEF and the EPD frameworks. Both studies have come across the same observations which is also in line with what was found in this study such as system boundary, modelling approach, allocation in multi-functional process and for recycling, cut-off and impact categories. However, there are some additional findings that Del Borghi et al. (2019) and Durão et al. (2020) have discussed which are not being brought up or observed in this study.

In terms of impact assessment, Del Borghi et al. (2019) found that both PEF and EPD do not consider carbon storage. This contrasts with the REDII framework, which allows the emission saving from carbon capture and storage/replacement. Del Borghi et al. also found that only climate change and photochemical ozone formation impact categories are comparable in PEF and EPD. The differences in impact categories were only lightly touched upon in this study as we decided to focus more on climate change. In addition to this finding in Del Borghi et al., we could also notice that eutrophication and acidification, which are two of the impact categories that PEF and EPD have in common, do not have the same unit. Eutrophication in EPD is indicated by kg PO_4^{3-}-eq, while in PEF, it is indicated by using N or P depending on which emission compartment is in concern. For acidification, the impact is indicated by kg SO_2-eq in EPD, while it is mol H^+-eq in PEF. This emphasizes further that PEF, EPD and REDII results cannot be compared as their methodologies are not in line with each other.

Del Borghi et al. (2019) also bring up another aspect of comparison regarding modelling approach in each framework. EPD uses ALCA, which has its advantage for the concept of modularity. This means that LCA done according to the EPD framework can be used to build a bigger LCA where many parts of products are involved (Zackrisson, 2021).

Durão et al. (2020) mention benchmarks in PEF, which are "PEF results for a representative product of the product category, available in PEFCRs". Durão considers benchmarks to be a good advantage of the PEF since it enables positioning of the product as well as verification of the probable results, which is not possible in EPD. Connecting to our study, the REDII provides typical and default values for emissions from some life cycle stages (cultivation, processing, transportation and distribution), which can be considered as benchmarks to compare the calculated results. Since there are no PEFCR for biofuels, benchmarking was not brought up and conducted in this study.

Furthermore, both Del Borghi et al. (2019) and Durão et al. (2020) bring up the PEF's requirement of hotspot identification in the interpretation of results. This makes PEF a good tool for companies to identify areas of improvement of a product as well as monitoring their environmental benefits. Lastly, both literatures also focus more on the formality of the two frameworks such as verification, dealing with data gaps and reporting, which were disregarded in this study.

In summary, this study has covered most critical discrepancies that both literatures have pointed out. In addition, the study includes the REDII in the comparison, which can bring additional findings and nuances to the comparison of existing environmental frameworks. The focus in our study also lies on the quantitative results when the three frameworks are applied. The results in this study can therefore be valuable for fuel producers and possibly to other actors that may be affected by a potential change in future regulations. We have also provided some practical aspects of the application of the three frameworks, which can contribute to development or improvement in the methodologies.

9. Conclusion

To conclude, there are differences between the PEF, EPD and REDII frameworks that leads to different results when applied to a case study. Those differences are the choice of allocation method when secondary material is used, allocation hierarchy for multifunctional processes, the number of elementary flows and impact categories that needs to be assessed, the CFs, the accounting of biogenic CO_2 and the downstream process. The case study of HVO from UCO shows that the PEF framework gives the highest climate change impact, whereas the REDII framework gives the lowest impact. The differences in the results come primarily from different interpretations of waste/secondary material in the frameworks when UCO is used, which lead to a big difference in system boundaries.

The top contributor for the PEF is the upstream processes of the palm oil production while for the EPD and the REDII, the hydrogen production is the top contributor. Furthermore, it was found that Swedish UCO is the most environmentally preferred choice compared to UCO from China and therefore the recommended alternative for Preem and other fuel producers.

However, the results may have some uncertainties partly because there is no PEFCR or PCR available for biofuels, which has left room for our own interpretations. PEFCR and PCR are important since it would give a more accurate interpretation of methodologies in the PEF and EPD frameworks.

9.1 Recommendations of framework

Depending on if an environmental study is performed by or on the behalf of a company, a government or an organization, different framework may be more or less suitable for the client's purpose. Using the case study of HVO from UCO as an example, for companies, the EPD or the REDII framework would be the most beneficial for companies if waste or secondary material is used as a feedstock in the product. A cut-off would be applied to the system, which gives a lower environmental impact comparing to the PEF. In other words, EPD and REDII encourage the use of secondary material more than PEF. Thus, the company may use the result of the study for market or regulation purposes. However, making waste or secondary too attractive can give rise to indirect problems as mentioned previously with the increasing demand for UCO.

On the other hand, the PEF framework may be more suitable for governments and organizations to use as it looks at the bigger picture by including several more environmental impact categories. It can be seen in our study that the PEF result is significantly higher than the EPD and REDII result. This is because while the PEF methodology encourage the use of secondary material, the framework also shows an awareness that the secondary material can lead to a problem in the future. Hence, it does not consider the secondary material to have zero burden upstream. As a result, the PEF can arguably provide a more accurate representation of the environmental impact of a product's life cycle compared to the other two frameworks. This in turn means that the PEF framework benefits the ecosystem and society rather than the biofuel producers. In addition, as the PEF framework is more comprehensive and complicated to use, the extra resources the PEF framework required may be too much to handle for smaller companies.

Furthermore, as it is shown in the case study, all three framework gives different environmental impacts due to the differences in methodologies, therefore the results cannot be compared to each other. In the future, the EC may require PEF to be the standard framework within EU. Therefore, the methodology in the EPD and possibly in the REDII may need to be revised in order to make the calculation in line and more comparable with the PEF framework. However, for the PEF to be applicable on a larger scale, a library of PEFCRs for many more product categories needs to be available.

9.2 Further recommendations

There are some areas that could be investigated further in this study. Firstly, the EPD international has updated its GPI to version 4.0, where some methodologies have been revised for example in the allocation for recycling. It would be interesting to see if the improvements in the EPD framework have become more in line with the PEF or not. Also, it was mentioned that the JRC has published a document about suggestions for updating the PEF method (Zampori & Pant, 2019). This document could be investigated further to see if the suggestions in the PEF's method would mean that the framework will become easier for users to use and understand.

Some aspects in all three frameworks that have been excluded in the scope of this study such as data quality assessment, the importance of modelling of electricity, interpretation of results, reporting and verification process. These aspects could be looked more into details. Furthermore, if a PEFCR and PCR for biofuels is available in the future, it would be interesting to remodel the case study again and compare the results to our study.

References

Arvidsson, R., Persson, S., Fröling, M., & Svanström, M. (2011). Life cycle assessment of hydrotreated vegetable oil from rape, oil palm and Jatropha. *Journal of Cleaner Production*, *19*(2-3), 129-137.

Biofuels International. (2021). *Germany remains the most important rapeseed producer in the EU.* https://biofuels-news.com/news/germany-remains-the-most-important-rapeseed-producer-in-the-eu/

Behrends, F.J. (2018). *Greenhouse gas footprint of biodiesel production from used cooking oils* (Master thesis). Retrieved from https://dspace.library.uu.nl/handle/1874/371109

Baumann, Henrikke, & Tillman, Anne-Marie. (2004). *The hitch hiker's guide to LCA: An orientation in life cycle assessment methodology and application.* Lund, Sweden: Studentlitteratur

Biodiesel prices (SME & FAME). (2021). *Biodiesel prices (SME & FAME).* Neste. https://www.neste.com/investors/market-data/biodiesel-prices-sme-fame#3a6f866e

Brander, Tipper, Hutchison, Davis. (2008) *Technical Paper | Consequential and Attributional Approaches to LCA: a Guide to Policy Makers with Specific Reference to Greenhouse Gas LCA of Biofuels* Ecometrica. http://www.globalbioenergy.org/uploads/media/0804_Ecometrica_-_Consequential_and_attributional_approaches_to_LCA.pdf

BSI. (2011*). PAS 2050 - Specification for the assessment of the life cycle greenhouse gas emissions of 720 goods and services*. The British Standards Institution 2011. https://shop.bsigroup.com/upload/shop/download/pas/pas2050.pdf

BSI. (2012*). PAS2050-1:2012 Assessment of life cycle greenhouse gas emissions from horticultural products.* The British Standards Institution 2012. https://shop.bsigroup.com/upload/Shop/Download/PAS/PAS2050-1.pdf

Chen, H., & Chen, G,Q. (2011). *Energy cost of rapeseed-based biodiesel as alternative energy in China*. Renewable Energy. 36(5), 1374-1378. https://doi.org/10.1016/j.renene.2010.11.026

Chen, P. (2016). *How to Process Used Cooking oil into Bio-diesel feedstocks: 5 steps.* Linkedin. https://www.linkedin.com/pulse/how-process-used-cooking-oil-bio-diesel5-steps-mark-xiao

Chen P. (2019). *Where and how to source qualified UCO suppliers in China.* Linkedin. https://www.linkedin.com/pulse/where-how-source-qualified-uco-suppliers-china-peter-chen/?trk=read_related_article-card_title

Del Borghi, A., Moreschi, L. & Gallo, M. (2019). Communication through ecolabels: how discrepancies between the EU PEF and EPD schemes could affect outcome consistency. *The International Journal of Life Cycle Assessment,* 25**,** 905–920. https://doi.org/10.1007/s11367-019-01609-7

Directive 2018/2001. *The promotion of the use of energy from renewable sources*. European Parliament, Council of the European Union. https://eur-lex.europa.eu/eli/dir/2018/2001/oj

Drost, R. (2020). *Are you prepared for the Product Environmental Footprints?*. Ecochain. https://ecochain.com/knowledge/are-you-prepared-for-the-product-environmental-footprint/

Durão, V., Silvestre, J.D., Mateus R., de Brito, J. (2020). Assessment and communication of the environmental performance of construction products in Europe: Comparison between PEF and EN 15804 compliant EPD schemes. *Resources, Conservation and Recycling*, 156. https://doi.org/10.1016/j.resconrec.2020.104703.

EPD International. (2019). *General Programme Instructions for the International EPD® System*. Version 3.01. www.environdec.com.

ETIP Bioenergy.(n.d.). Hydrotreatment to HVO. Retrieved 2 March 2021, from https://www.etipbioenergy.eu/value-chains/conversion-technologies/conventional-technologies/hydrotreatment-to-hvo

European Commission. (2012). *Product Environmental Footprint (PEF) Guide.* Italy: Joint Research Centre.

European Commission. (2018). *PEFCR Guidance document, - Guidance for the 13 development of Product Environmental Footprint Category Rules (PEFCRs)*. version 6.3.

European Commission. (2020). *Voluntary Schemes.* Retrieved 12 May 2021, from https://ec.europa.eu/energy/topics/renewable-energy/biofuels/voluntary-schemes_en?redir=1

European Commission. (2021). *Renewable energy directive.* Retrieved 7 February 2021, from https://ec.europa.eu/energy/topics/renewable-energy/renewable-energy-directive/overview_en

European Commission. (n.d.). *Renewable Energy – Recast to 2030 (RED II).* https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii

Hallberg et al. (2013). *Setup of f3 data network for Well-to-wheel (method and) LCI data for fossil and renewable fuels in the Swedish market*. f3 - Swedish Knowledge Centre for Renewable Transportation Fuels. www.f3centre.se

International Monetary Fund. (2021a). *Global price of Palm Oil [PPOILUSDQ]*, Federal Reserve Bank of St. Louis. Retrieved May 5, 2021 from https://fred.stlouisfed.org/series/PPOILUSDQ

International Monetary Fund. (2021b). *Global price of Rapeseed Oil [PROILUSDM]*. Federal Reserve Bank of St. Louis. Retrieved May 5, 2021 from https://fred.stlouisfed.org/series/PROILUSDM

Jungbluth, N., Sutter, J., Faist Emmenegger, M., Dinkel, F., Stettler, C., Doka, G., Chudacoff, M., Dauriat, A., Gnansounou, E., Spielmann, M., Kljun, N., & Keller, M. (2007). *Life Cycle Inventories of Bioenergy*. *Data v2.0 (2007)*. Ecoinvent. https://www.researchgate.net/publication/313056035_Life_Cycle_Inventories_of_Bioenergy_Data_v20_2007

Karlsson, H. et al. (2020). *HVO Produced from Swedish Raw Materials - Current and Future Potentials*. Report No. FDOS 07:2020. F3 The Swedish Knowledge Centre for Renewable Transportation Fuels.

Källmén, A., *et. al*., (2019) *Well-to-wheel LCI data for HVO fuels on the Swedish market.* Report No 2019:04, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. Available at www.f3centre.se.

Li, Y., Fine, F., Fabiano-Tixier, A.S., Abert-Vian, M., Carre, P., Pages, X., & Chemat, F. (2014). *Evaluation of alternative solvents for improvement of oil extraction from rapeseeds.* Comptes Rendus Chimie, 17(3), 242-251. https://doi.org/10.1016/j.crci.2013.09.002

Lorenzi, G., Mignini, L., Venezia, B., Silva C., & Santarelli, M,. (2018). *Integration of high-temperature electrolysis in an HVO production process using waste vegetable oil*. Energy Procedia, 158, 2005-2011. https://www.sciencedirect.com/science/article/pii/S1876610219304886

My Fuel Cell. (2021). Framställning av vätgas. Retrieved 1 March 2021, from https://www.myfuelcell.se/framst%C3%A4llning-av-v%C3%A4tgas

Nairn, C. (2020, November 17). *Best Type of Forest for CO2 Storage Depends on Location and Climate, Study Finds*. EcoWatch. https://www.ecowatch.com/best-forest-carbon-storage-2648952882.html

Neste. (2014). *Hydrotreated vegetable oil (HVO) – premium renewable biofuel for diesel engines*. Neste.

Nikander, S. (2008). Greenhouse gas and energy intensity of product chain: case transport biofuel. *Master's thesis. Helsinki University of Technology*.

OECD. (1972). *The Polluter-Pays Principle: OECD Analyses and Recommendations.* https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=OCDE/GD(92)81&docLanguage=En

PCR 2020:05 Basic products from forestry version 1.0

Phillips, D. (2019). *Implications of Imported Used Cooking Oil (UCO) as a Biodiesel Feedstock.* The Bioeconomy Consultants NNFCC. https://www.nnfcc.co.uk/files/mydocs/UCO%20Report.pdf

Plantations International. (n.d.). Palm Oil. Retrieved 1 March 2021, from https://www.plantationsinternational.com/palm-oil/

Poon, D. (2019). *UCO Collection Potential in China* [Powerpoint slides]. ISCC. https://www.iscc-system.org/wp-content/uploads/2019/07/7.-Dannis-Poon_ECO_UCO-Potential-in-China.pdf

Queiroz, A. G., França, L., & Ponte, M. X. (2012). The life cycle assessment of biodiesel from palm oil ("dendê") in the Amazon. *Biomass and bioenergy*, *36*, 50-59.

Rapid Transition Alliance. (2018, December). *How China brought its forests back to life in a decade.* https://www.rapidtransition.org/stories/how-china-brought-its-forests-back-to-life-in-a-decade/

Schmidt, J. (2007). Life cycle assessment of rapeseed oil and palm oil: Ph. D. thesis, Part 3: Life cycle inventory of rapeseed oil and palm oil.

Schmidt, J., & De Rosa, M. (2020). Certified palm oil reduces greenhouse gas emissions compared to non-certified. *Journal of Cleaner Production*, *277*, 124045.

Shahbandeh. (2021a). *Consumption of vegetable oils worldwide from 2013/14 to 2020/2021, by oil type.* Statista. https://www.statista.com/statistics/263937/vegetable-oils-global-consumption/

Shahbandeh. (2021b). *Leading producing countries of rapeseed in 2019/2020 (in million metric tons)**. Statista. https://www.statista.com/statistics/263930/worldwide-production-of-rapeseed-by-country/

Shahbandeh. (2021c). *Worldwide production major vegetable oils, 2012-2021*. Statista. https://www.statista.com/statistics/263933/production-of-vegetable-oils-worldwide-since-2000/

Stichnothe, H., & Schuchardt, F. (2011*). Life cycle assessment of two palm oil production systems*. Biomass and bioenergy, *35*(9), 3976-3984.

Socfin, (n.d.) Palm oil. Retrieved 1 March 2021, from https://www.socfin.com/en/palm-oil

Svensk Fettåtervinning. (n.d.a). *Kvalitets- och miljöcertifierad återvinning av uttjänta frityroljor, stek- och grillfetter*. Retrieved 30 March 2021, from http://www.fettatervinning.se/res/Default/Foretagsinformation.pdf

Svensk Fettåtervinning. (n.d.b). *Fettåtervinning – vad är det?*. Retrieved 30 March 2021, from http://www.fettatervinning.se/Fettatervinning.htm

Svensk Fettåtervining. (n.d.c). *Om oss*. Retrieved 30 March 2021, from http://www.fettatervinning.se/Omoss.htm

Swedgas. (2020). *Gaskvaliteten följs noggrant* [Excel sheet].https://www.swedegas.se/gas/gaskvalitet

Tan, Y. A., Halimah, M., Zulkifli, H., Vijaya, S., Puah, C. W., Chong, C. L., ... & Choo, Y. M. (2010). Life cycle assessment of refined palm oil production and fractionation (Part 4). *J. Oil Palm Res*, *22*, 913-926.

Transport & Environment. (2020). REDII and advanced biofuels. https://www.transportenvironment.org/sites/te/files/publications/2020_05_REDII_and_advanced_biofuels_briefing.pdf

Voora, V., Larrea, C., Bermúdez,, S., & Baliño, S. (2020). *Global Market Report: Palm Oil*. International Institute for Sustainable Development. Retrieved from https://www.iisd.org/publications/global-market-report-palm-oil

Warman, E., Iqbal, M. N., & Fahmi, F. (2019, May). Efficiency analysis of electric energy use in palm oil processing (case study Bandar Pulau). In *IOP Conference Series: Materials Science and Engineering* (Vol. 505, No. 1, p. 012048). IOP Publishing. From https://iopscience.iop.org/article/10.1088/1757-899X/505/1/012048/pdf

Wolf, M.A., Hofstra, U., Vroege, G.J., Schryver, A.D., & Zampori, L. (2019, 10, 08). Circular Footprint Formula [slide 11]. European Commission. https://ec.europa.eu/environment/eussd/pdf/Webinar%20CFF%20Circular%20Footprint%20Formula_final-shown_8Oct2019.pdf

WWF. (2020). 8 things to know about palm oil. Retrieved 1 March 2021, from https://www.wwf.org.uk/updates/8-things-know-about-palm-oil

WWF. (n.d.). *What is Palm Oil? Facts About the Palm Oil Industry*. Retrieved 1 March 2021, from https://www.worldwildlife.org/industries/palm-oil

Workman, D. (2021). Palm Oil Imports by Country. Retrieved 1 March 2021, from http://www.worldstopexports.com/palm-oil-imports-by-country/

Zackrisson, M. (2021*). Life cycle assessment of electric vehicle batteries and new technologies* [Doctoral thesis, KTH Royal Institute of Technology]. KTH Royal Institute of Technology. http://kth.diva-portal.org/smash/get/diva2:1554513/FULLTEXT01.pdf

Zampori, L., Pant, R. (2019). *Suggestions for updating the Product Environmental Footprint (PEF) method*. Joint Research Centre. https://doi.org/10.2760/424613

Appendix A

Part 1: Agricultural modelling

The PEFCR guidance v6.3 describes how agricultural products shall be modelled. Data such as yield, water, land use, land use change, fertilizer amount (artificial and organic, N, P) and pesticide amount (per active ingredients) should be included. The data should be crop-type specific and country-region-or- climate specific.

Cultivation data shall be collected over a timespan that is enough to provide an average assessment. It shall follow the LEAP guideline: Environmental Performance of Animal Feeds Supply Chain. Hence, for annual crops, the assessment period shall be at least three years. If the data is not available due to the new production system, the timespan can be shorter but should not be less than one year. For perennial plants, the data used shall be a steady state. In other words, it shall represent all the development stages involved in the studied period. The LEAP guideline shall also be used as rules to handle multifunctional processes.

Pesticide emission shall be modelled as specific active ingredients. The USEtox can be used as the impact assessment method. As a temporary approach, the pesticides applied on the field shall be modelled as 90% emitted to the agricultural soil compartment, 9% to air and 1 % to water.

Fertilizer including manure emission shall be separated per fertilizer type and cover at least:

- NH_3, N_2O - from N-fertilizer application to air;
- NO_3 - leaching from N-fertilizer application to water unspecified;
- CO_2 - from lime, urea and urea-compounds application to air;
- PO_4 - leaching and runoff of soluble phosphate from P-fertilizer application to water unspecified or freshwater; and
- P - soil particles containing phosphorus from P-fertilizer application to water unspecified or freshwater.

The freshwater eutrophication impact category shall be modelled starting after the run-off i.e. when P leaves the agricultural land. The Life Cycle Inventory (LCI) should be modelled as the amount of P emitted to water. Thus, the emission compartment should be water. If this is not available, the LCI may be modelled as the amount of P applied to the agricultural land and the emission compartment is soil.

The marine eutrophication starts after N leaves the soil. Thus, emission of N to soil shall not be modelled. The emission of N accumulated in the air and water compartment per amount of N-fertilizer applied on the field shall be modelled. The N fertilizer application excludes external sources such as rain deposition. For the sake of consistency, fixed number of emission factors are determined following a simplified approach. The emission factors are described in Table 14 in the PEFCR guidance v.6.3.

Part 2: GHGs emission from land use change

The PEF-framework requires that the emissions arising from land use change (LUC) shall be accounted according to the PAS 2050: 2011 (BSI, 2011) and to be complemented with PAS 2050-1:2012 (BSI, 2012) for horticultural product. In this study, the PAS 2050-1:2012 is the most relevant guideline. The guideline shows that the calculation can be done both when the previous land use change is known and unknown. The calculation methods are described as following:

Land use change for known previous land use

The GHG emissions shall include GHG emissions and removals from vegetation and soil carbon stock changes. The assessment is to be done based on the previous land use and the current land use according to the IPCC Guidelines for National GHG Inventories. The PAS 2050:2012 also states that *"the carbon stock change shall be linearly amortised during a period of 20 years. All GHG emissions form land use change shall be attributed to crop production"*

Land use change for unknown previous land use

the PAS 2050:2012 provides some equations which can be used to calculate average GHG emissions from land use change in cases where the previous land use change is unknown, but the crop type and country are known. The calculation can be made based on four type of land use in a period of 20 years prior to the assessment. The four land use types are forest, grassland, perennial cropland and annual cropland. Two types of values are to be calculated: i) the average land use change and ii) the weighted country average of transforming the four land use types in a certain country to either perennial or annual cropland. The highest value of the GHG emissions among the two alternatives shall be used.

For the calculation of the average and weighted average, the rate of expansion (and contraction) is done based on the share of area expansion during 20 years prior to the assessment. The data on land use shall be obtained from the United Nations Food and Agriculture Organization (FAO). The calculation starts from the most recent year in the database. The change in land use is then calculated by comparing an average of crop area in three most recent years to an average of the three oldest years.

In case of no expansion, the crop has no land use change attribution. The expansion of cropland can be indicated by calculating the share of area expansion in relation to total area of the assessed crop or REC. If the REC-value is negative, no further calculation needs to be done.

The value of REC can be calculated as:

$$REC = \frac{expanded\ area\ of\ assessed\ crop\ (ha)}{current\ area\ of\ assessed\ crop\ (ha)} \tag{1}$$

The equations for the calculation of the GHG emissions from land use change is presented as followed.

Average land use change

- If the assessed crop is an annual crop:

  $$LUC = \frac{1}{3} \times \Delta GHG_{fa} + \frac{1}{3} \times \Delta GHG_{ga} + \frac{1}{3} \times \Delta GHG_{pa} \tag{2}$$

  Where:

  ΔGHG_{fa} = GHG emissions due to the transformation of forest to annual cropland
  ΔGHG_{ga} = GHG emissions due to the transformation of grassland to annual cropland
  ΔGHG_{pa} = GHG emission due to the transformation of perennial to annual cropland

- If the assessed crop is a perennial crop:

  $$LUC = \frac{1}{3} \times \Delta GHG_{fp} + \frac{1}{3} \times \Delta GHG_{gp} + \frac{1}{3} \times \Delta GHG_{pp} \tag{3}$$

  Where:

  ΔGHG_{fa} = GHG emissions due to the transformation of forest to perennial cropland
  ΔGHG_{ga} = GHG emissions due to the transformation of grassland to perennial cropland

ΔGHG_{ap} = GHG emission due to the transformation of annual to perennial cropland

Weighted average land use change

- If the assessed crop is an annual crop:
  $$LUC = SF \times \Delta GHG_{fa} + SG \times \Delta GHG_{ga} + SP \times \Delta GHG_{pa} + SA \times \Delta GHG_{aa} \qquad (4)$$
- If the assessed crop is a perennial crop:
  $$LUC = SF \times \Delta GHG_{fp} + SG \times \Delta GHG_{gp} + SP \times \Delta GHG_{pp} + SA \times \Delta GHG_{ap} \qquad (5)$$

Where:
SF = Shere LUC from forest land
SG = Share LUC from grassland
SP = Share of LUC from perennial cropland
SA = Share of LUC from annual cropland

The parameter SF, SG, SP and SA can be calculated according to the following:

$$SF = SEF \times REC \qquad (6)$$
$$SG = SEG \times REC \qquad (7)$$
$$SP = SEP \times REC \qquad (8)$$
$$SA = SEA \times REC \qquad (9)$$

Where:
SEF = Share of area expansion at the expense of forest land
SEG = Share of area expansion at the expense of grassland
SEP = Share of area expansion at the expense of perennial cropland
SEA = Share of area expansion at the expense of annual cropland
REC = Share of area expansion in relation to total area of the assessed crop

The parameter SEF, SEG, SEP and SEA can be calculated according to the following:

$$SEF = SEF\&G \times \frac{contraction\ forest\ (ha)}{contraction\ forest\ and\ grassland\ (ha)} \qquad (10)$$

$$SEG = SEF\&G \times \frac{contraction\ grassland\ (ha)}{contraction\ forest\ and\ grassland\ (ha)} \qquad (11)$$

$$SEP = (1 - SEF\&G) \times \frac{sum\ contraction\ perennial\ crops\ (ha)}{sum\ contraction\ all\ crops\ (ha)} \qquad (12)$$

$$SEA = (1 - SEF\&G) \times \frac{sum\ contraction\ annual\ crops\ (ha)}{sum\ contraction\ all\ crops\ (ha)} \qquad (13)$$

The parameter SEF& G is the combined decline in forest and grassland, which can be calculated according to equation (14).

$$SEF\&G = 1 - \frac{the\ sum\ of\ all\ crop\ area\ contractions\ (ha)}{the\ sum\ of\ all\ crop\ area\ expansion\ (ha)} \qquad (14)$$

If the SEF&G is negative, the SEF and SEG shall be set to zero.

Accounting of GHG emissions from lands use change

The GHG emissions from land use change arise from a change in vegetation and soil carbon stocks. In order to find these emissions for the assessed crop, the following data are needed:

- Default reference of soil organic carbon stocks based on climate and soil type (IPCC Guidelines, Volume 4, Table 2.3).
- Factor for soil carbon stock change, assumed full tillage and medium input level (IPCC Guidelines, Volume 4, Table 5.5).
- An average of carbon stocks in forest and grassland vegetation of existing forest type. This can be calculated by using:
    - Share of different types of forest per country, determined by FAO (Global Forest Resource Assessment 2000)
    - Default vegetation biomass per forest and grassland type (IPCC Guidelines, Volume 4, Table 4.7 and Table 6.4)
    - Default carbon fraction for forest (IPCC Guidelines, Volume 4, Table 4.3) and carbon fraction of biomass in general, which is 0.5 ton C per ton biomass.

The IPCC has no default values for carbon stocks in vegetation of specific crop. Thus, it is assumed that the carbon stock of annual crop is roughly 1 ton of dry matter per ha and for the perennial crop the carbon stock is assumed to be 20 tons of dry matter per ha. To find the average LUC for the assessed crop, the Equation (2) and (3) shall be multiplied with the share of area expansion in relation to total area of the assessed crop (REC).

Appendix B

Explanation of parameters in REDII calculations (Directive 2018/2001/EU)

Emission from cultivation

The value of e_{ec} consider emissions from: cultivation process, production of chemicals or products used in the cultivation process, collection, drying, storage of raw materials, waste and leakage. The CO2 capture in the cultivation of raw material is excluded.

Emission from processing

The value of e_p includes emission from the production of the biofuels i.e. from waste and leakages and from the production of chemicals or material used in the processes including the CO_2 emission corresponding to the carbon contents of fossil inputs, regardless of whether it is combusted or not.

The electricity used in the process is not produced within the fuel production plant, the GHG emissions intensity of the production and distribution of that electricity is assumed to be average emission specific to the defined region.

Emission from transport and distribution

The value of e_{td} includes emission from the transport of raw and semi-finished materials and from the storage and distribution of finished products. The transportation during the cultivation or extraction of raw materials is not included in this parameter.

Annualized emission caused by land-use change

The value of e_l is calculated by equally dividing the total emissions over 20 years, as shown in Equation 12.

$$e_l = (CS_R - CS_A) \times 3{,}664 \times 1/20 \times 1/P - e_B \qquad \text{(Equation 12)}$$

where

e_l = annualized GHG emissions from carbon stock change due to land-use change (measured as gCO2eq/MJ of biofuel or bioliquid. Cropland and perennial cropland shall be regarded as one land use;

CS_R = the carbon stock per unit area associated with the reference land-use (measured as mass (tonnes) of carbon per unit area, including both soil and vegetation). The reference land-use shall be the land-use in January 2008 or 20 years before the raw material was obtained, whichever was the later;

CS_A = the carbon stock per unit area associated with the actual land-use (measured as mass (tonnes) of carbon per unit area, including both soil and vegetation). In cases where the carbon stock accumulates over more than one year, the value attributed to CSA shall be the estimated stock per unit area after 20 years or when the crop reaches maturity, whichever the earlier;

P = the productivity of the crop (measured as biofuel or bioliquid energy per unit area per year) and

e_B = bonus of 29 g CO_2eq/MJ biofuel or bioliquid if biomass is obtained from restored degraded land.

Emission saving from soil carbon accumulation

The GHG saving from improved agriculture management, e_{sca}, such as improved crop rotation, the use of manure and compost to increase soil organic content shall be taken into account there is verifiable evidence that proves that the soil carbon has increased or is expected to increase.

Emission saving from fuel in use

Emission from the fuel in use, e_u, is zero if it is biofuels or bioliquids. In case of non-CO_2 GHG i.e. N_2O and CH_4, the fuel in use is to be included in the e_u factor for bioliquids.

Emission saving from CO2 capture and geological storage

Emission saving from CO_2 capture and geological storage, e_{ccs}, is calculated from those that have not taken into account in e_p and they shall be limited to the avoided emissions that are directly related to the extraction, transport, processing and distribution of fuel if stored in compliance with the Directive 2009/31/EC.

Emission saving from CO2 capture and replacement

Emission saving from CO_2 capture and replacement, e_{ccr}, is calculated from the direct emission saving through the production of biofuels or bioliquids they are attributed to and limited to the capture of CO_2 that originates from biomass, in which it replaces fossil-derived CO_2.

Appendix C

Part 1: Calculation of phosphate emission in Chinese rapeseed

The leaching of phosphate to water can be found by calculating the surplus of P in the crop and account 2.9% of the surplus as phosphate. The P-content in a crop is 6.2 g/kg rapeseed. The P-content of rapeseed straw is not considered in this case. Assume that 5 kg/ha of seed is required as input. The input of P2O5 fertilizer is 67.5 kg/ha, which correspond to 29.48 kg/ha P. The calculation of the phosphate emission is shown in Table 18.

Table 18.Calculation of phosphate emission from cultivation of rapeseed oil in China

Input	**Quantity(kg/ha)**	**P-content (kg P/ha)**
Seed	5.0	3E-02
P-fertiliser	29.5	29.5
Total P output		29.5
Output	**Quantity(kg/ha)**	**P-content (kg P/ha)**
Harvested rapeseed	2025.1	12.6
Balance		
P surplus	17.0	17.0
P leaching (2.9%)	0.5	0.5

Part 2: Calculation of land use change (LUC) for case study

The case study used PAS 2050-1:2012 to calculate the GHGs emissions from the land use change of the cultivation of palm and rapeseed. The palm fruit cultivation was assumed to take place in Indonesia and Malaysia. The rapeseed cultivation was assumed to take place in Germany. There is no emissions from LUC for the rapeseed cultivated in China as the calculation of REC is negative. The data obtained from FAOSTAT such as forest, pasture and meadows (assumed to be the same as grassland) and crop areas for all crops in the country were obtained from between 2018-2016 and between 1999-2001.

LUC from palm cultivation

The data on carbon stock of soil and vegetation are:

- Area harvested of all individual crops in Indonesia and Malaysia from 2018-2016 and from 1999-2001 (crops data, FAOSTAT).
- Forest land and land under permanent meadows and pastures in Indonesia and Malaysia from 2018-2016 and from 1999-2001 (land use data, FAOSTAT).
- Default reference of soil organic carbon stocks for climate zone “tropical wet” with soil type “sandy soils” corresponds to 66 t C/ha (IPCC Guidelines, Volume 4, Table 2.3).
- The IPCC Guideline, Volume 4, Table 5.5 provides a relative stock change factors over 20 years for different management activities on cropland. The default values for type of land use “perennial/tree crop”, type of tillage “full” and level of input “medium” are 1. Hence the factor for soil carbon stocks is $1 \times 1 \times 1 = 1$.
- Average share of natural forest and planted forest (in Indonesia and Malaysia) is 0.908 and 0.092 respectively (Global Forest Resource Assessment 2000).

- Default above ground biomass in forests for “tropical rainforest” in continent “Asia (insular)” is 350 (280-520) ton d.m./ha. In the calculation 350 ton d.m./ha was used (IPCC Guidelines, Volume 4, Table 4.7).

- Default biomass stock on grassland (above and below ground, non woody biomass) for “tropical – moist &wet” is 6.2 ton d.m./ha (IPCC Guidelines, Volume 4, Table 6.4).

- Default carbon fraction of above ground forest biomass is 0.47 ton C/ton d.m. (IPCC Guidelines, Volume 4, Table 4.3).

- General carbon fraction of biomass is 0.5 ton C/ ton biomass.

The data above were used to calculate different parameters and GHG emissions. The values of the calculated parameters are shown in Table 19. The calculation of average and weighted average emissions from LUC are shown in Table 20.

Table 19. Parameters used for the calculation of LUC of palm cultivation in Indonesia and Malaysia

Parameters	**Indonesia**	**Malaysia**	**Average**
REC	0.8	0.3	0.6
SEF&G	0.9	0.6	0.8
SEF	0.9	0.6	0.8
SEG	0.02	0	0.02
SEP	0.004	0.3	0.2
SEA	0.1	0.02	0.1
SF	0.7	0.2	0.5
SG	0.01	0	0.007
SP	0.004	0.1	0.06
SA	0.09	0.007	0.05

Table 20. Demonstration of the calculation of GHG emission for LUC of palm cultivation in Indonesia and Malaysia

For forest and grassland			
Reference soil carbon stock	Tropical wet climate, sandy slits	66.0	ton C/ha
Factor for soil carbon stock change	Perennial crop* full tillage * medium input level	1.0	-
Resulting carbon stock change	66-(1*66)	0	ton C/ha
LUC from soil carbon stock change (LUCf&g)	0*(44/12)*(1/20)	**0**	ton CO_2 eq/ha*yr
For forest			
Reference vegetation carbon stock	350 ton biomass/ha*0.47 kg C/kg biomass	164.5	ton C/ha
Current vegetation carbon stock	default perennial	9.4	ton C/ha

LUC from vegetation carbon stock change (LUCfp)	(164.5-9.4)*(44/12)*(1/20)	28.4	ton CO_2 eq/ha*yr
ΔGHG_{fp}	LUCfp + LUCf&g	**28.4**	
For grassland			
Reference vegetation carbon stock	16.1 ton biomass/ha*0.47 kg C/kg biomass	7.6	ton C/ha
Current vegetation carbon stock	default perennial	9.4	ton C/ha
LUC from vegetation carbon stock change (LUCgp)	(7.57-9.4)*(44/12)*(1/20)	-0.3	ton CO_2 eq/ha*yr
ΔGHG_{gp}	LUCgp + LUCf&g	**-0.3**	
For perennial tree crops			
Reference vegetation carbon stock	20 ton biomass/ha*0.47 kg C/kg biomass	9.4	ton C/ha
Current vegetation carbon stock	default perennial	9.4	ton C/ha
LUC from vegetation carbon stock change (LUCpp)	(9.4-9.4)*(44/12)*(1/20)	**0**	ton CO_2 eq/ha*yr
ΔGHG_{pp}	LUCpp	**0**	ton CO_2 eq/ha*yr
For annual crop			
Reference vegetation carbon stock	4 ton biomass/ha*0.47 kg C/kg biomass	1.9	ton C/ha
Current vegetation carbon stock	default perennial	9.4	ton C/ha
LUC from vegetation carbon stock change	(1.9-9.4)*(44/12)*(1/20)	-1.4	ton CO_2 eq/ha*yr
Reference soil carbon stock	Tropical wet climate, sandy slits	31.0	ton C/ha
Factor for soil carbon stock change	Perennial crop* full tillage * medium input level	1.0	
Resulting carbon stock change	31-(0.47*66)	-0.02	ton C/ha
LUC from soil carbon stock change	(-)0.02*(44/12)*(1/20)	-3.7E-03	
Total LUC from annual crop	LUC from soil and vegetation (annual crop)	**-1.4**	ton CO_2 eq/ha*yr
ΔGHG_{ap}	LUC from soil and vegetation (annual crop)	**-1.4**	ton CO_2 eq/ha*yr
The weighted average	(SF* ΔGHG_{fp})+(SG* ΔGHG_{gp})+(SP* ΔGHG_{pp})+(SA* ΔGHG_{ap})	**13.5**	ton CO_2 eq/ha*yr
Average LUC	REC* (1/3* ΔGHG_{fp})+(1/3* ΔGHG_{gp})+(1/3* ΔGHG_{ap})	**5.3**	ton CO_2 eq/ha*yr

Table 20 shows that the weighted average LUC is higher than average LUC. Hence the weighted average value LUC was used for the cultivation of palm fruit in this study.

LUC from rapeseed cultivation

The data on carbon stock of soil and vegetation are:

- Area harvested of all individual crops in Germany from 2018-2016 and from 1999-2001 (crops data, FAOSTAT).
- Forest land and land under permanent meadows and pastures in Germany from 2018-2016 and from 1999-2001 (land use data, FAOSTAT).

- Default reference of soil organic carbon stocks for climate zone “cold temperate, moist” and soil type of “HAC soils” and “sandy soils” has a soil organic carbon (SOC) corresponds to 95 and 71 t C/ha respectively (IPCC Guidelines, Volume 4, Table 2.3). An average value of the two SOC was take, which corresponds to 83 t C/ha.

- The IPCC Guideline, Volume 4, Table 5.5 provides a relative stock change factors over 20 years for different management activities on cropland. The default values for type of land use “long term cultivated, temperate/boreal” is 0.69, and 1 for type of tillage “full” and level of input “medium”. Hence the factor for soil carbon stocks is $0.69 \times 1 \times 1 = 0.69$.

- Average share of natural forest and planted forest in Germany is 1 and 0 respectively (Global Forest Resource Assessment 2000).

- Default above ground biomass in forests for “temperate continental forest” in continent “Asia, Europe (≤20 y)” is 20 ton d.m./ha (IPCC Guidelines, Volume 4, Table 4.7).

- Default biomass stock on grassland (above and below ground, non woody biomass) for “cold temperate – moist &wet” is 13.6 ton d.m./ha (IPCC Guidelines, Volume 4, Table 6.4).

- Default carbon fraction of above ground forest biomass is 0.47 ton C/ton d.m. (IPCC Guidelines, Volume 4, Table 4.3).

- General carbon fraction of biomass is 0.5 ton C/ ton biomass.

The data above were used to calculate different parameters and GHG emissions. The values of the calculated parameters are shown in Table 21. The calculation of average and weighted average emissions from LUC are shown in Table 22.

Table 21. Parameters used for the calculation of LUC from rapeseed cultivation in Germany.

Parameters	**Germany**
REC	0.1
SEF&G	-1.2
SEF	0
SEG	0
SEP	0.1
SEA	0.9
SF	0
SG	0
SP	0.01
SA	0.1

Table 22. Demonstration of the calculation of GHG emission for LUC of rapeseed cultivation in Germany.

For forest and grassland and perennial tree crops			
Reference soil carbon stock	Cold temperate, moist	83.0	ton C/ha
Factor for soil carbon stock change	Annual crop* full tillage * medium input level	0.69	-
Resulting carbon stock change	83-(0.69*83)	25.7	ton C/ha
LUC from soil carbon stock change (LUCf&g)	25.73*(44/12)*(1/20)	**4.7**	ton CO_2 eq/ha*yr
For forest			
Reference vegetation carbon stock	20 ton biomass/ha*0.47 kg C/kg biomass	9.4	ton C/ha
Current vegetation carbon stock	default annual	1.9	ton C/ha
LUC from vegetation carbon stock change (LUCfa)	(9.4-1.9)*(44/12)*(1/20)	1.4	ton CO_2 eq/ha*yr
ΔGHG_{fa}	LUCf&g + LUCfa	**6.1**	ton CO_2 eq/ha*yr
For grassland			
Reference vegetation carbon stock	13.6 ton biomass/ha*0.47 kg C/kg biomass	6.4	ton C/ha
Current vegetation carbon stock	default annual	1.9	ton C/ha
LUC from vegetation carbon stock change (LUCga)	(6.392-1.9)*(44/12)*(1/20)	0.8	ton CO_2 eq/ha*yr
ΔGHG_{ga}	LUCf&g + LUCga	**5.5**	ton CO_2 eq/ha*yr
For perennial tree crops			
Reference vegetation carbon stock	20 ton biomass/ha*0.47 kg C/kg biomass	9.4	ton C/ha
Current vegetation carbon stock	default annual	1.9	ton C/ha
LUC from vegetation carbon stock change (LUCpa)	(9.4-9.4)*(44/12)*(1/20)	1.4	ton CO_2 eq/ha*yr
ΔGHG_{pa}	LUCf&g + LUCpa	**6.1**	ton CO_2 eq/ha*yr
For annual crop			
Reference vegetation carbon stock	4 ton biomass/ha*0.47 kg C/kg biomass	1.9	ton C/ha
Current vegetation carbon stock	default annual	1.9	ton C/ha
LUC from vegetation carbon stock change	(1.9-1.9)*(44/12)*(1/20)	0	ton CO_2 eq/ha*yr
ΔGHG_{aa}	LUCaa	0	ton CO_2 eq/ha*yr
The weighted average	(SP* ΔGHG_{pa})+(SA* ΔGHG_{aa})	**7.4E-02**	ton CO_2 eq/ha*yr
Average LUC	REC *(1/3* ΔGHG_{fa})+(1/3* ΔGHG_{ga})+(1/3* ΔGHG_{pa})	**0.7**	ton CO_2 eq/ha*yr

Table 22 shows that the average LUC is higher than the weighted average LUC. Hence the average value LUC was used for the cultivation of rapeseed in this study.

Appendix D

Data on the production of HVO from 100% used RSO and 100% used PO.

Table 19. Inventory data of the production of HVO from 100% used rapeseed oil

Description	**Quantity**	**Unit**
Input		
Used rape seed oil	1.0	ton
H_2	3.4E-02	ton
Electricity	14.0	kWh/ ton UCO
Fuel gas (from by-products)	270.0	MJ/ ton UCO
Output		
HVO	0.9	ton
C_3H_8	0.05	ton
CH_4	6E-03	ton
H_2O	0.1	ton
Steam (net production)	6E-02	ton

Table 20. Inventory data of the production of HVO from 100% used palm oil

Description	**Quantity**	**Unit**
Input		
Used palm oil	1.0	ton
H_2	3.0E-02	ton
Electricity	14.0	kWh/ ton UCO
Fuel gas (from by-products)	270.0	MJ/ ton UCO
Output		
HVO	0.8	ton
C_3H_8	5.2E-02	ton
CH_4	7E-04	ton
H_2O	0.1	ton
Steam (net production)	6E-02	ton/ ton UCO

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY