PUBLICATION FDOS 20:2021

Final report

ENVIRONMENTAL AND TECHNO-ECONOMIC ASSESSMENT OF ALTERNATIVE PRODUCTION PATHWAYS FOR SWEDISH DOMESTIC HVO PRODUCTION

December 2021

Hanna Karlsson Potter, Torun Hammar and Kajsa Henryson
Dept. of Energy and Technology, Swedish University of Agricultural Sciences (SLU)

Theo Nyberg, Pavinee Nojpanya, Sofia Poulikidou and Julia Hansson
IVL Swedish Environmental Research Institute

A project within

RENEWABLE TRANSPORTATION FUELS AND SYSTEMS 2018-2021

A collaborative research program between the Swedish Energy Agency and
f3-The Swedish Knowledge Centre for Renewable Transportation Fuels

www.energimyndigheten.se

THE SWEDISH KNOWLEDGE CENTRE FOR RENEWABLE TRANSPORTATION FUELS

www.f3centre.se

PREFACE

The work described in this report comes from a project carried out within the collaborative research program *Renewable transportation fuels and systems* (Förnybara drivmedel och system), Project no. 46980-1, *Sustainable HVO production potential and environmental impact*. The project was funded by the Swedish Energy Agency and f3 Swedish Knowledge Centre for Renewable Transportation Fuels.

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

f3-Swedish Knowledge Centre for Renewable Transportation Fuels is a networking organization focusing on development of environmentally, economically, and socially sustainable renewable fuels. The f3 center is funded jointly by the center's partners and the region of Västra Götaland. Chalmers Industriteknik functions as the host for the f3 organization (www.f3centre.se/en/about-f3).

The project group consisted of research groups from the Swedish University of Agricultural Sciences and IVL-Swedish Environmental Research Institute. A reference group with representatives from the Swedish and international HVO markets also participated in the project.

This report presents the results from the second part of the project, *Sustainable HVO production potential and environmental impact*, where the environmental impact and economic potential of alternative HVO production in Sweden were assessed.

This report should be cited as:

Karlsson Potter, H., *et. al*., (2021) *Environmental and Techno-Economic Assessment of Alternative Production Pathways for Swedish Domestic HVO production.* Publ. No FDOS 20:2021. Available at https://f3centre.se/en/renewable-transportation-fuels-and-systems/

ABBREVIATIONS

AC	Ash content
AD	Anaerobic digestion
AGTP	Absolute global temperature change potential
CAPEX	Capital expenditure
CEPCI	Chemical engineering plant cost index
CHP	Combined heat and power
COD	Chemical oxygen demand
DM	Dry matter
EU	European Union
FAME	Fatty acid methyl esters
GHG	Greenhouse gases
GWP	Global warming potential
HHV	Higher heating value
HVO	Hydrotreated vegetable oil
ICBM	Introductory carbon balance model
ISO	International Standardization Organisation
K	Potassium
LCA	Life cycle assessment
LHV	Lower heating value
MC	Moisture content
MO	Microbial oil
N	Nitrogen
OPEX	Operation
P	Phosphors
PFAD	Palm fatty acid distillate
RED	Renewable Energy Directive
RED II	Renewable Energy Directive II
SEK	Swedish kronor
SF	Scale factor
SOC	Soil organic carbon
t	Tonne (1000 kg)
TDC	Total direct capital cost
TIC	Total indirect capital cost

EXECUTIVE SUMMARY

Hydrotreated vegetable oil (HVO) is currently the dominant liquid biofuel on the Swedish market for transportation fuels. This HVO is largely imported into Sweden and concerns regarding the environmental impact, especially of HVO produced from palm oil, have been raised.

The aim of this report is to present an environmental and techno-economic assessment of alternative production pathways for Swedish domestic HVO production. The report builds on the potential study conducted by Karlsson Potter *et al.* (2020) also within the research project *Sustainable HVO – production potential and environmental impact*. From that study, two raw materials and pathways for future HVO production were selected:

- System I: Camelina. HVO produced from the winter oil crop *Camelina sativa* grown as a cover crop not directly competing with other crops.
- System II: Forest residues. HVO produced from treetops and branches by biochemical conversion using oleaginous yeast.

For both systems, environmental and techno-economic assessments were performed using a life cycle perspective. For the techno-economic assessment, three indicators were considered: i) investment cost based on capital expenditure (CAPEX); ii) operating cost (OPEX); and iii) revenues from co-products. These indicators were used to estimate the total cost of oil to be used in the HVO process (both camelina oil and microbial oil from forest residues). Data for the assessment was taken from existing literature and studies examining similar systems. The focus of the economic assessment was on oil production, while the process from oil to HVO was excluded. Camelina oil and microbial oil were considered to be of similar quality, and thus processing to HVO was not expected to influence the final HVO quality and cost. The focus of the environmental assessment was climate impact, which was assessed in two ways: (1) following the EU Renewable Energy Directive (called the RED II method); and (2) following the ISO standard for life cycle assessment (LCA) (called the ISO method). Two different climate metrics were used for both methods: (1) Global Warming Potential (GWP), which is the most commonly used metric; and (2) Absolute Global Temperature Change Potential (AGTP), which better illustrates the climate impact over time.

The estimated total cost of the oil was found to be 5.01 SEK L^{-1} for camelina oil and 9.6 SEK L^{-1} for microbial oil. This cost is estimated based an oil production capacity of about 22 000 tonnes (t) oil $year^{-1}$ from each system that results in a feedstock demand of 50 000 t $year^{-1}$ camelina seeds and 200 000 t $year^{-1}$ forest residues. Feedstock prices and production capacity influence the final cost to a great extent. Other important parameters influencing the final cost included market potential and selling price of co-products such as electricity or biogas.

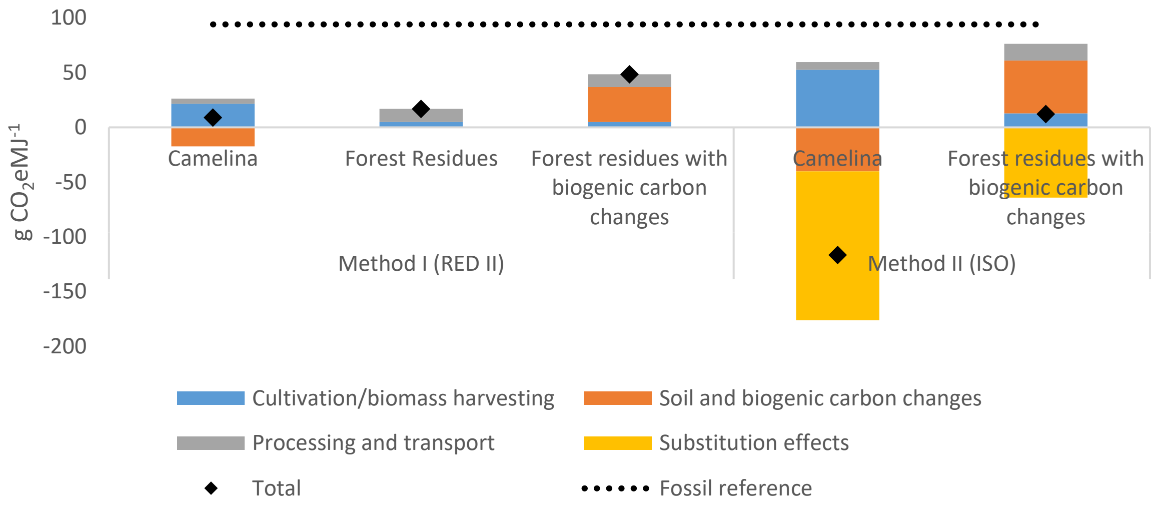


Figure 1. Climate impact of hydrotreated vegetable oil (HVO) produced from camelina and forest residues, calculated with the method in the EU Renewable Energy Directive (RED II, Method I) and with the ISO method that handles co-product with system expansion (Method II).

For the climate impact assessment, the results showed that, when applying RED II methodology, HVO produced from camelina (system I) had greenhouse gas (GHG) reduction potential (compared with a fossil fuel reference) of 90 % when including climate benefits from increased soil carbon accumulation, and 72 % reduction potential without this effect (Figure 1). For HVO produced from forest residues (System II), the reduction potential was 82 % when applying the RED II methodology. Using the ISO method resulted in large reduction potential values compared with fossil fuels (Figure 1). Changes in biogenic carbon stocks and substitution effects from production of by-products strongly influenced the results. Analysis of climate impact over time (using the AGTP climate metric) showed that camelina HVO had an immediate climate benefit compared with a fossil reference, while HVO produced from forest residues showed a higher climate impact than the fossil reference over the first 30 years when analyzed from a stand perspective.

SAMMANFATTNING

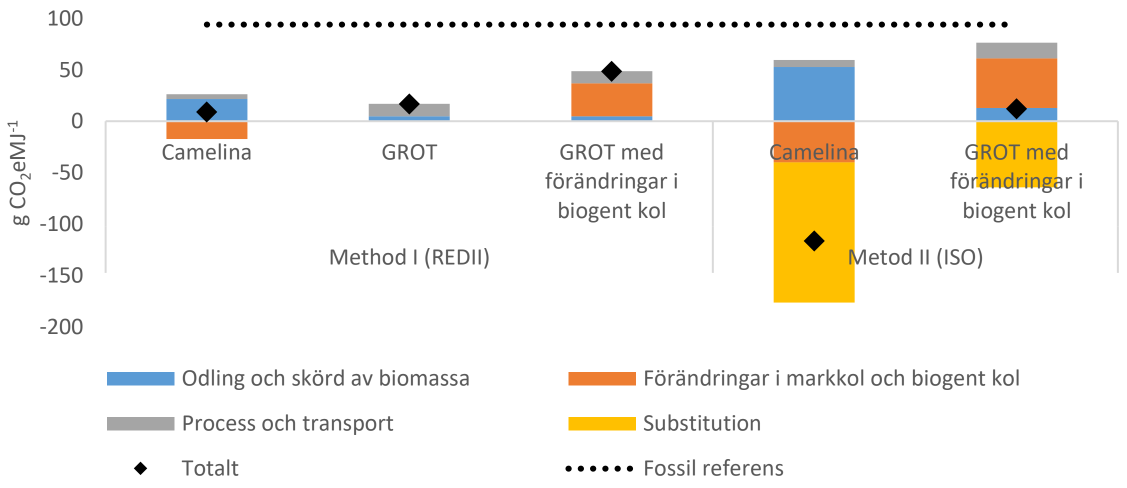
Vätebehandlade vegetabiliska oljor (HVO) är idag det dominerande flytande biobränslet på den svenska marknaden. HVO importeras i stor utsträckning till Sverige och farhågor beträffande miljöpåverkan från framför allt HVO producerad från palmolja har lyfts.

Denna rapport bygger på potentialstudien (Karlsson Potter *et al.*, 2020) som gjorts inom forskningsprojektet ”Hållbar HVO-produktion, potential och miljöpåverkan”. Baserat på Karlsson Potter *et al.* (2020) valdes två råvaror för framtida HVO-produktion ut för vidare studier. De utvalda råvarorna var:

- System I Camelina: HVO producerat från oljegrödan camelina sativa odlad som en fånggröda vilket gör att den inte direkt konkurrerar med andra grödor.
- System II GROT: HVO producerat från toppar och grenar (GROT) via biokemisk omvandling av lignocellulosa till olja med hjälp av oljejäst.

Miljö- och teknikekonomisk analys genomfördes för båda systemen. Miljöanalysen fokuserade på klimatpåverkan vilken bedömdes med två metoder med livscykelperspektiv: (1) Förnybartdirektivet (RED II); och (2) ISO-standarden för livscykelanalys (LCA). Dessutom användes två olika metoder för att uppskattat klimatpåverkan: (1) *Global Warming Potential* (GWP), vilket är den vanligaste metoden för att uppskatta klimatpåverkan; och (2) *Absolute Global Temperature Change Potential* (AGTP), den senare för att visa klimatpåverkan över tid.

För den teknoekonomiska bedömningen inkluderades tre indikatorer: i) investeringskostnad (CAPEX), ii) driftskostnad (OPEX) och iii) intäkter från samprodukter. Dessa indikatorer användes för att beräkna den totala kostnaden för oljan som senare kommer att användas i HVO-processen. Vidare förädling till HVO inkluderades inte i den teknoekonomiska bedömningen då denna förädling förväntas vara liknande för båda systemen.



Figur 1 (sv.). Klimatpåverkan för HVO som produceras av camelina och skogsrester beräknat med metoden i direktivet om förnybar energi (RED II) och med ISO-metoden som hanterar samprodukt med systemutvidgning.

Den totala oljekostnaden beräknades till 5,01 SEK/L för camelinaoljan och 9,6 SEK/L för mikrobiell olja från GROT. Råvarupriserna och produktionskapaciteten påverkade i hög grad slutkostnaden. Andra viktiga aspekter var marknadspotentialen och försäljningspriset på samprodukterna som el eller biogas. Klimatanalysen visade att HVO producerat från camelina har potential att reducera växthusgasutsläppen (från en referens för fossila bränslen) med 90 %, då effekten av en ökad markkolackumulering räknades med och 72 % utan denna effekt, när RED II-metodiken användes (Figur 1(sv.)). För HVO producerat av skogsrester (system II) var minskningspotentialen 82 % vid tillämpning av RED II-metoden. När klimatpåverkan beräknades med ISO-metoden resulterade båda systemen i betydande reduktionspotential, jämfört med fossila bränslen (Figur 1(sv.)). Resultaten påverkades av hur utsläppen av biogent kol hanteras samt hantering av bi-produkter och potentiell substitution. Analysen av klimatpåverkan över tid (med hjälp av klimatmåttet AGTP) visade att camelina-HVO hade en omedelbar klimatnytta jämfört med en fossilreferens, medan HVO producerat av skogsrester visade en högre klimatpåverkan än fossilreferensen i över 30 år då den analyserades ur ett beståndsperspektiv.

CONTENTS

1 INTRODUCTION

Sweden, with its ambitious climate targets, has the highest share of renewable fuels in the transport sector of all European countries (EEA, 2021). The liquid biofuels used on the Swedish market are dominated by fuels produced from fatty acids in the form of hydrotreated vegetable oil (HVO) and fatty acid methyl esters (FAME). HVO is among the most important liquid biofuel (Energimyndigheten, 2020). The advantage of HVO is that it can be used as drop-in fuel in diesel engines and blended with fossil diesel to very high rates, this rate can in some cases be limited by requirements on density and cold weather properties (Holmgren *et al.*, 2021). Use of fossil fuels and associated greenhouse gas (GHG) emissions in road transport, including heavy transport, can thereby be decreased while maintaining current infrastructure such as fuel distribution system and vehicle fleet. However, future potential for HVO production is projected to be limited, due to limited availability of fatty acids for biofuel production (Panoutsou, 2021). The demand for renewable fuels within aviation and marine transports can also contribute to increased demand for fatty acids. The main raw materials used to produce HVO used in Sweden in 2019 were slaughterhouse waste (42 %), palm fatty acid distillate (PFAD) (36 %), palm oil (8 %), and tall oil (14 %) (Energimyndigheten, 2020). In that year, 95 % of raw materials used to produce the HVO sold on the Swedish market originated from countries outside Sweden, and often outside Europe (Energimyndigheten, 2020). Environmental concerns have been raised regarding current HVO production, especially biofuel production from palm oil and by-products from palm oil production (*e.g.*, PFAD) (Mukherjee & Sovacool, 2014). As regards the economic performance of HVO, the cost of HVO production varies considerably depending on the feedstock used. Since capital and operational costs have tended to fall over time, the cost of feedstock for alternative production pathways for HVO production is expected to become an important parameter of the overall cost function (Brown *et al.*, 2020). There is an urgent need for a clearer understanding of the supply potential of domestic raw materials for HVO production, and especially of raw materials that can increase the opportunities for continuous, sustainable, and economically feasible domestic HVO supply.

Within the research project *Sustainable HVO – production potential and environmental impact*, alternative raw materials and production pathways for HVO from Swedish domestic feedstock were identified (Figure 2). Potential HVO production from these feedstocks today (2020) and in 2050 was assessed and it was concluded that the highest potential is for conversion of lignocellulosic materials to fatty acids, while raw materials already in use, such as waste cooking oils and animal fats, showed low potential when sourced within Sweden only (Karlsson Potter *et al.*, 2020). The project also showed that it would be challenging to cover the almost 13 TWh HVO used in 2019 in Sweden with domestic raw materials that are compliant with the European Renewable Energy Directive (RED II) (European Parliament, 2018), *i.e.*, not crops that can be used as food and feed for biofuel production, for which the Directive has set a cap of 7 %.

However, several alternative raw materials and production pathways can be considered. In the work described in this report, two of these were selected for further assessment of their techno-economic performance and environmental impact. These were: i) HVO produced from *Camelina sativa* (camelina) grown as a cover crop and ii) HVO produced from forest residues using biochemical conversion via oleaginous yeast.

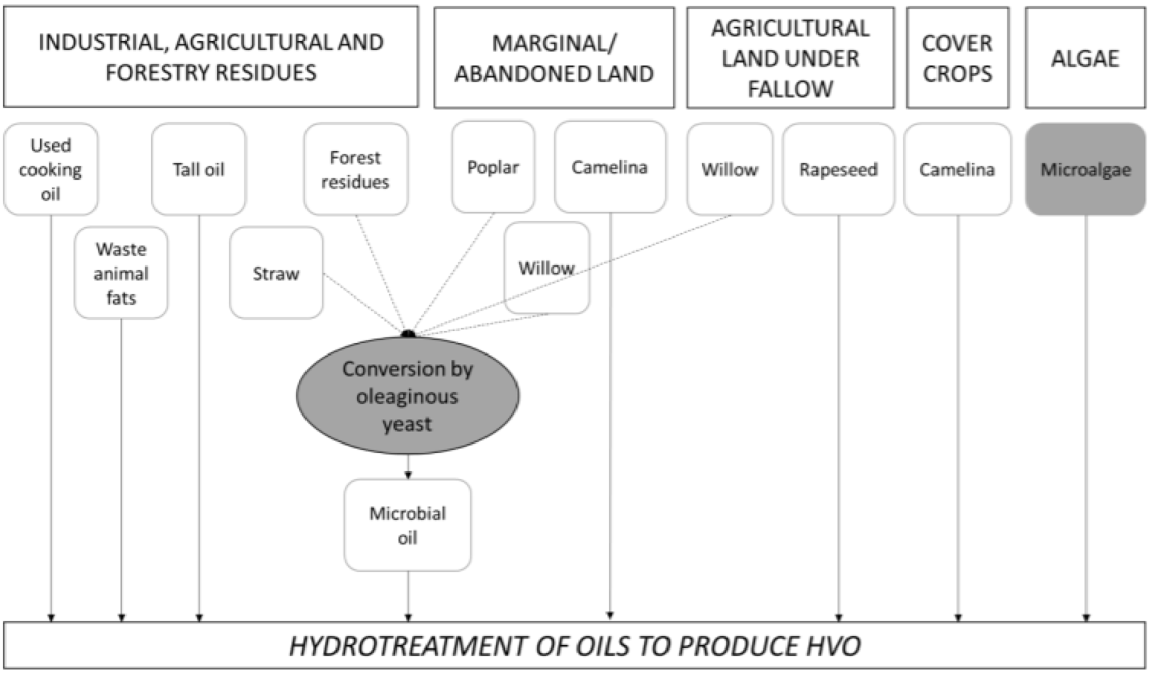


Figure 2. Illustration of raw materials and pathways assessed in an earlier part of the current research project (diagram taken from Karlsson Potter *et al.*, 2020).

Raw materials and pathways were selected based on the assessed production potentials in the earlier study (Karlsson Potter *et al.*, 2020) and in collaboration with the project reference group, which included representatives from the HVO producers Neste and Preem. Important aspects in the selection of the raw materials were production potential, agreement with RED II and the sustainability criteria for biofuels (European commission 2019), expected impacts on biodiversity and climate, that the production is not contributing to increase use of agricultural land and thereby risking indirect land use effects and the system's potential for increased overall resource use efficiency.

The aims of the present study were to identify and describe the two selected production pathways (further described below) and related process steps; to quantify the environmental impact in terms of climate change; and to assess the economic implications in terms of production cost. While the focus of the environmental assessment was on climate impact, other environmental aspects were considered (section 5.3).

1.1 SELECTED SYSTEMS FOR FURTHER ASSESSMENT

The following two systems were selected:

- System I: Camelina HVO production from the oil crop *Camelina sativa* grown as a cover crop not directly competing with other crops.
- System II: Forest residues. HVO production from tops and branches by biochemical conversion to yeast oil using oleaginous yeast.

System I: Camelina as a cover crop was selected due to its potential to increase resource use efficiency and productivity in Swedish agriculture, by allowing the same agricultural land to be used for several purposes. This system is also compliant with RED II, since cover crops fall under "Low indirect land use change risk" in RED II. However, cultivation of camelina requires extra inputs of *e.g.*, fertilizers and field operations, which are associated with environmental impacts. No published study was found on environmental and techno-economic aspects of growing camelina as a cover crop in Swedish crop rotations and processing camelina oil into HVO, which makes it interesting for further studies.

System II: Forest residues were selected since the future potential of forest residues was considered to be relatively high compared with that of other raw materials assessed by Karlsson Potter *et al.* (2020). Forest residues are an abundant and low-cost biomass that can be produced and harvested without extensive inputs such as pesticides and fertilizers. However, harvesting of forest residues for energy purposes is associated with changes in biogenic carbon flows, which has an impact on climate change (Hammar *et al.*, 2015). This affects fuel efficiency regarding climate change mitigation, so analysis is required of the climate impact of HVO from forest residues. *Forest residues* are defined here as the Swedish category 'GROT', *i.e.*, tops and branches (sometimes called slash) and not including stumps.

Research has shown that both camelina oil and microbial oil is suitable for hydrotreatment and further processing into biofuels including aviation fuels (i Nogue *et al.* 2018 and Tepelus *et al.* 2019).

1.2 STRUCTURE OF THE REPORT

The systems studied and underlying assumptions made in system design are presented in Chapter 2 of this report. Chapter 3 describes methodological decisions and assumptions used for the techno-economic assessment and the climate impact assessment. Data collection for the techno-economic and climate impact assessments is described in Chapter 4. The results are presented and discussed in Chapter 5, first for the techno-economic assessment of the two systems analyzed (section 5.1) and then for the climate impact assessment (section 5.2). Environmental impacts beyond climate impacts are highlighted in section 5.3, followed by a general discussion (section 5.4). Conclusions are presented in Chapter 6 and suggestions for future studies are made.

2 SYSTEM DESCRIPTIONS

2.1 SYSTEM I: HVO PRODUCED FROM *CAMELINA SATIVA* AS A COVER CROP

Intermediate crops, *i.e*., crops cultivated between main growing seasons, offer an opportunity to increase the output of agricultural land, while also providing environmental and agronomic benefits such as improved nutrient retention and increased soil fertility (Marcinkeviciene *et al.*, 2013; Fageria *et al.*, 2005). Cover crops are a type of intermediate crop mainly intended to cover the soil between growing seasons when the soil surface would otherwise be bare. In the strict definition, cover crops are not harvested and are therefore not used as food or feed (Alonso-Ayuso *et al.*, 2020). However, the term 'cover crop' is sometimes used for harvested intermediate crops and is also the term used in RED II (Blanco-Canqui *et al.*, 2020; European Parliament, 2018; Berti *et al.*, 2017b). Therefore in this report we also include harvested intermediate crops in the term 'cover crops'.

Oilseed cover crops have gained attention as potential biofuel feedstock, mainly because they can be cultivated without competing with food and feed crops (Sindelar *et al.*, 2017; Chammoun *et al.*, 2013; Krohn & Fripp, 2012). One oilseed crop that can be grown as a cover crop is *Camelina sativa* L. Crantz (camelina). It is an ancient native European species in the Brassica family that was used for its oil until about a century ago, when it was outcompeted by the higher yielding rapeseed (Zanetti *et al.*, 2021; Berti *et al.*, 2016). However, it has recently been proposed as an interesting alternative feedstock for biofuels due to its low input requirements, winter-hardiness, and high oil content (Krzyżaniak & Stolarski, 2019; Berti *et al.*, 2016). It could therefore be a viable cover crop to cultivate in Sweden, as it could provide vegetable oil without displacing current food and feed production. Camelina could also be grown on marginal lands which could be an option to increase vegetable oil production from Swedish agriculture. The potential production of vegetable oils on marginal lands using camelina was assessed by Karlsson Potter *et al*. (2020).

It is not completely clear how camelina grown as cover crop would be classified according to RED II, which only refers to cover crops as "non-food cellulosic material". On the one hand, camelina could be cultivated without displacing food and feed crops, with a low risk of causing land-use change. On the other hand, it could potentially be used as food or feed, even though it is currently not widely used for human consumption (Berti *et al.*, 2016). To our knowledge, there is no additional guidance on how to interpret RED II in this case. However, we deemed it sufficiently interesting to investigate its potential environmental performance as a biofuel in a Swedish context.

Several options for cultivating camelina between other crops in existing crop rotations were identified by Karlsson Potter *et al.* (2020). In the present study, camelina was assumed to be grown as a cover crop after spring barley and with a pea crop sown into the camelina, which is harvested before the peas (Figure 3). This is known as a relay cropping system. It is not fully known which pests affect camelina grown in Sweden, so we assumed that camelina only occurred every sixth year in the crop rotation, following the current recommendations for rapeseed. The cultivation was assumed to occur in Swedish agricultural region 3 (*Götalands norra slättbygder*).

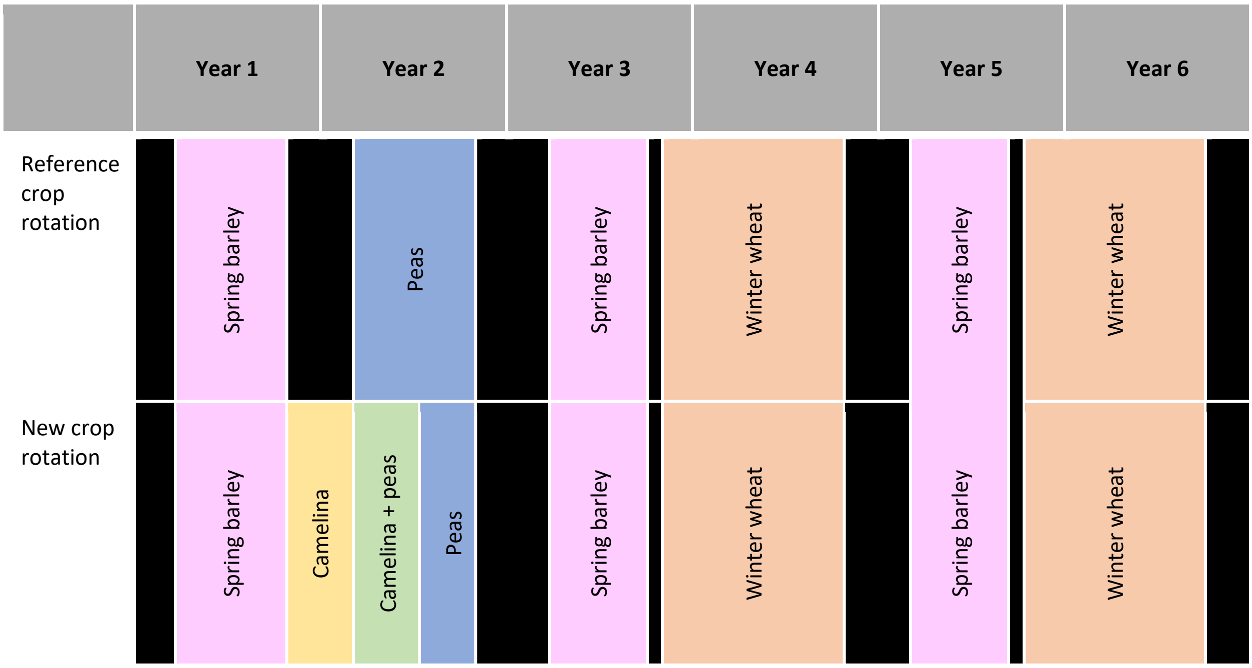


Figure 3. Schematic diagram of (top) the reference crop rotation without camelina and (bottom) the new crop rotation with camelina as a cover crop. Black boxes represent periods without crop cover.

The system studied is presented in Figure 4. After harvest, the camelina seeds were assumed to be transported to a separate facility for pressing and extraction of camelina oil. Previous studies have shown that the by-product obtained after oil extraction, camelina meal, could be used as animal feed, as is done with the leftover press cake and meals from extraction of several other vegetable oils (Lawrence *et al.*, 2016; Hixson *et al.*, 2014). After extraction, the camelina oil was assumed to be transported to an HVO production plant and hydrogenated into HVO.

Location of cultivation and processing

The following assumption were made on geographic location of cultivation and processing: cultivation took place in southern Sweden (production region 3, Götalands slättbygder), pressing of the oil around 100 km from the place of cultivation, HVO conversion took place in Gothenburg.

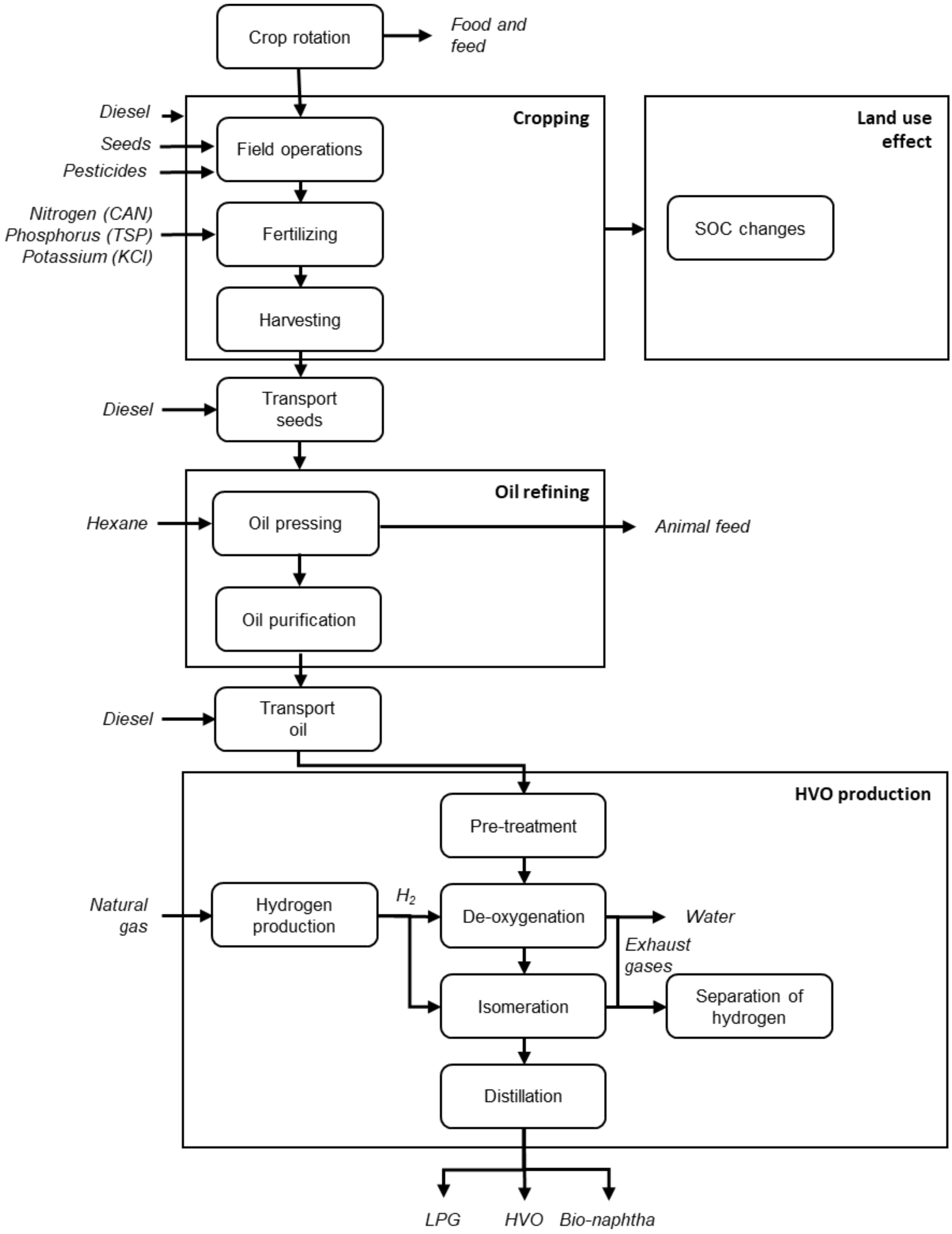


Figure 4. Flowchart of *System I*: Hydrotreated vegetable oil (HVO) produced from *Camelina sativa* grown as a cover crop. SOC=soil organic carbon.

2.2 SYSTEM II: HVO PRODUCED FROM FOREST RESIDUES (TOPS AND BRANCHES) USING OLEAGINOUS YEAST

In assessments performed in the earlier part of the research project, conversion of lignocellulosic materials to HVO production was identified as having the highest future potential for domestic HVO production (Karlsson Potter *et al.*, 2020).

The production pathway considered here uses oleaginous yeast to convert sugars to fatty acids. Oleaginous yeast can accumulate fatty acids to more than 20 % of its cell weight (Thorpe & Ratledge, 1972). To grow, the yeast needs a carbon source, commonly sugars, and many of the oleaginous yeast strains can use both C5 sugars and C6 sugars. Use of both types of sugars is important for efficient use of hydrolysate derived from lignocellulosic biomass. Lignocellulosic biomass consists of cellulose, which can be hydrolyzed to C6 sugars (mainly glucose), and hemicellulose, which can be hydrolyzed to C5 and C6 sugars.

The system studied is presented in Figure 5. The forest residues were assumed to be harvested, chipped, and transported to a biochemical conversion plant, where steam explosion and enzymatic hydrolysis were used for pretreating the biomass. The resulting sugars were assumed to be fermented using oleaginous yeast, resulting in production of fatty acids, hereafter called microbial oil (MO). The main by-products from the process are yeast biomass (residues from the MO extraction process) and lignin (residues from the pretreatment step). The yeast biomass was assumed to be anaerobically digested to produce biogas that was upgraded for use as transportation fuel. The lignin was assumed to be combusted in a combined heat and power plant (CHP) to produce electricity and heat required in the facility, with some surplus electricity that could be sold. After MO production in the biochemical conversion plant, the MO was assumed to be transported to a HVO plant, where it was converted to HVO. The biochemical conversion plant was assumed to be located close to the forest harvesting site, which in this case was assumed to be in Dalarna, Sweden, as it is representative of central Swedish conditions in estimations of degradation rate and forest growth rate. Transportation of oil is far less bulky than transporting the wood chips, and transportation of oil from Dalarna to the southern Swedish port of Gothenburg was included.

Location of forest residue harvesting and processing

The following assumption were made around the location of biomass harvesting and further processing to HVO: The forest residues were harvested in the region of Dalarna in the middle part of Sweden, an average transportation distance of 60 km of forest residues from harvest site to biochemical conversion site was assumed, HVO conversion was assumed to take place in Gothenburg.

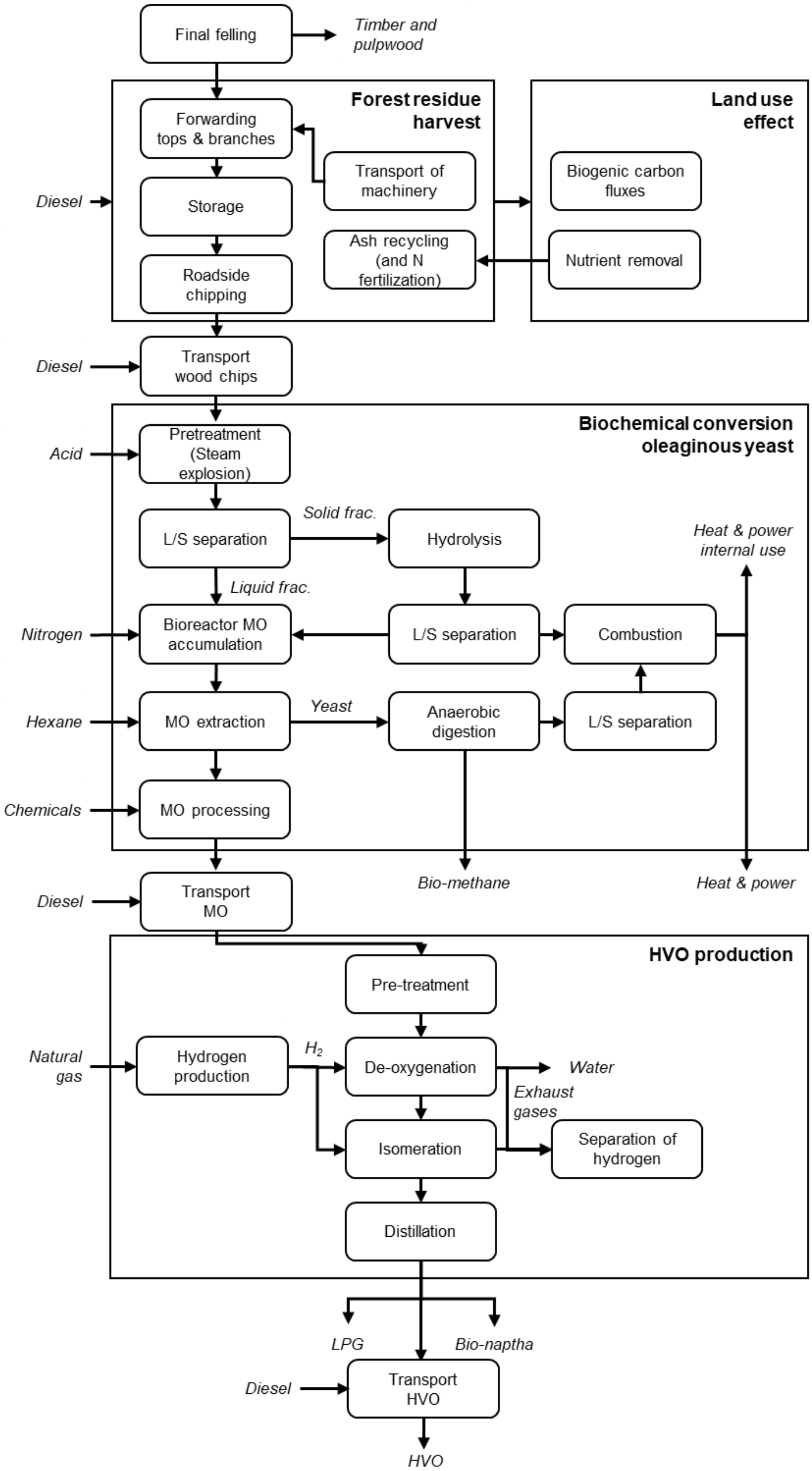


Figure 5. Flowchart of *System II:* Hydrotreated vegetable oil (HVO) produced from forest residues (tops and branches) using oleaginous yeast. MO=microbial oil.

3 METHOD

The two selected HVO production pathways were assessed from a systems perspective, investigating both the techno-economic and environmental performance. The respective methods and indicators used are described in the following sections.

3.1 TECHNO-ECONOMIC ANALYSIS

3.1.1 Material and energy balances

Mass and energy balances for the two HVO production pathways were estimated based on data obtained from the literature or specific calculations performed using the process simulation software Aspen PlusTM V11. The results and detailed information are presented in Chapter 4 and Appendix 1.

3.1.2 Economic assessment

For the economic assessment, three indicators were considered:

- Investment cost based on capital expenditure (CAPEX)
- Operating cost (OPEX)
- Revenue from by-products and/or residue streams

These indicators were used to calculate the total cost of oil going to the HVO process for both camelina oil and MO oil from forest residues. The focus of the economic assessment was on oil production, while the transformation process from oil to HVO was excluded. It is assumed that conversion to HVO will take place in existing HVO production facilities while specific variations and potential adjustments needed will depend on the biorefinery and types of oils used that is not possible to define at this stage.

CAPEX

Investment cost based on capital expenditure (CAPEX) is an estimate of the initial investment needed for all activities to prepare the plant and plant site, including "designing, constructing, installing [and commissioning] a plant" (Zimmermann *et al.*, 2020). Several methods for estimation of CAPEX can be used, depending on the level and quality of data available. A detailed CAPEX estimation can thus be rather complex and include uncertainties, especially for processes where detailed data are lacking, *i.e.*, processes in the development stage. Equation (1) shows the different costs that were included in estimation of CAPEX in this study:

$$CAPEX = TDC + TIC \qquad (1)$$

where *TDC* is total direct capital costs and *TIC* is total indirect capital costs.

TDC includes the costs of *e.g.*, equipment, buildings, and installation, while TIC can be considered as a start-up cost of the investment. In this study, TIC was assumed to be 5 % of TDC. CAPEX estimates for the oil production plant were made using literature values taken from studies with similar technologies as reference. These literature values were then adjusted in terms of reference year and plant size, to obtain estimates of CAPEX that corresponded to the processes in the present case. The adjustment from reference year was made to account for differences in plant construction costs between years. It was done using the Chemical Engineering Plant Cost Index (CEPCI), which has updated values for each year. Plant size was accounted for by scaling the cost according to the ratio of reference capacity and the capacity of the case plant, using a scale factor (SF) to consider potential effects of economies of scale.

The equation used for adjusting CAPEX from the reference value ($CAPEX_{ref}$) to the estimate for the assessed case ($CAPEX_{case}$) was:

$$CAPEX_{case} = CAPEX_{ref} \times \frac{CEPCI_{case}}{CEPCI_{ref}} \times \left(\frac{Capacity_{case}}{Capacity_{ref}}\right)^{SF} \tag{2}$$

where SF represent a scale factor, In the case of camelina oil, the reference value was taken from Mupondwa *et al.* (2016), where 2016 was used as the reference year. In the case of MO, the reference value was extracted from Koutinas *et al.* (2014), Olofsson *et al.* (2017), and Barta *et al.* (2010), and 2010 was used as the reference year.

The scale factor of 0.6 was applied and 2020 was used as the base year for conversion of currency and for the CEPCI adjustment.

OPEX

Operating cost (OPEX) refers to operational expenditure and considers both variable costs and fixed costs (Zimmermann *et al.*, 2020). Variable costs depend on the amount of product produced and include *e.g.* costs for raw materials, energy, utilities, and more. Fixed costs include *e.g.* salaries and costs that are not directly dependent on the amount of product output.

Two different approaches were used to estimate the annual OPEX of production of camelina oil and MO. A more simplified approach was used to estimate OPEX of the camelina oil process. Using literature values from similar studies, the share of OPEX as a percentage of CAPEX was calculated and used as a reference value. This percentage covers all operational expenditure (fixed and variable) except the cost of feedstock for camelina oil and MO, which is camelina seeds and forest residues, respectively.

To calculate OPEX for the camelina oil bioconversion plant, the reference percentage was applied in combination with the corresponding CAPEX estimated through the procedure described above. The feedstock cost is not included in this OPEX, to facilitate for a separate sensitivity analysis of this cost, considering that it makes up a large share of total OPEX (SEK $year^{-1}$). Total OPEX for the camelina oil was thus calculated as:

$$OPEX_{tot} = OPEX_{feedstock} + OPEX_{rest} = (Feedstock\ cost \times Annual\ feedstock\ use)$$

$$+(\% \times CAPEX)\ [\text{SEK year}^{-1}] \tag{3}$$

Based on the estimation by Mupondwa *et al.* (2016), OPEX comprised 137% of CAPEX.

For the MO process, OPEX was estimated using a bottom-up approach where it was assumed that consumption of energy and material was the dominant cost in OPEX. Hence, by calculating the amount of energy and material used in the modelled processes per year, the annual OPEX was found. The reason for using this bottom-up approach, rather than the form of estimation used for the camelina system, was lack of data. Data for a bottom-up approach were available from other parts of this project. The MO process include a CHP which met all the energy demand for the process, so OPEX of the MO process consisted only of the cost of material, excluding feedstock cost and other kinds of OPEX such as labor cost.

Revenue from by-products

Production of camelina oil and MO results in by-products, which can be sold on the market to generate revenue. Extraction of camelina oil produces camelina meal that can be used as animal feed. In this study, it was assumed that camelina meal had the same price as soybean meal. Production of MO generates biogas and excess electricity as by-products. The annual revenues from these by-products were subtracted from the annualized CAPEX and OPEX, to obtain the annual cost of the process. Although the exact utilization level and respective prices for the by-products is uncertain, it is considered an important parameter of the overall feasibility and economic sustainability of the suggested production processes. The effects of price variations are, however, investigated as sensitivity analysis.

Cost of oil

Using the CAPEX and annual OPEX values for the bioconversion plants, the cost of oil was calculated for both systems. The cost of oil per energy unit or volume can simply be described as all costs (CAPEX and OPEX) for producing the oil, divided by the amount of oil produced. However, since some costs are spread out over the lifetime of the plant while some occur at one single moment, time discounting is required in order to make the costs comparable. One way of doing this is by calculating the annual CAPEX and adding this to the annual OPEX (which is estimated in annual form to begin with). Time discounting requires deciding on a discount rate, which captures the relative preference of money in time. A high discount rate gives less value to future money than a low discount rate. For the discount rate, *r*, and the CAPEX, expressed as *I*, the annual CAPEX expressed as *C* can be calculated for a discount period of *n* years according to:

$$C = I\frac{r(1+r)^n}{(1+r)^n-1} \tag{4}$$

To calculate the cost of oil, data on annual costs and annual production of oil are needed. The annual CAPEX is calculated using time discounting, based on a discount rate (assumed to be 6 % in this study). The levelized cost of oil, expressed in SEK L^{-1} oil, was calculated as:

$$Cost\ of\ oil = \frac{Annualized\ CAPEX + OPEX - revenues}{Annual\ amount\ of\ oil\ produced\ over\ lifetime} \tag{5}$$

Sensitivity analysis of the techno-economic model

A sensitivity analysis was performed to investigate variations in the assumptions made. Parameters related to the economic assessment model were modified and the impact on the cost of camelina oil and MO was assessed. The input parameters varied were the unit price of feedstocks, *i.e.*, camelina seeds and forest residues, the plant capacity, OPEX (excluding feedstock costs) and the market price of by-products.

3.1.3 Key assumptions and delimitations

Assumptions made for the camelina and forest residues systems in the techno-economic assessment, based on previous studies and discussions with industry representatives, are presented in Table 1. Only feedstock that can be sourced in Sweden or in the Nordic countries was considered. As such, there were constraints in relation to annual oil production and capacity of the respective plants. The study followed the work and estimations presented in previous work (Karlsson Potter *et al*., 2020). The assumed capacity of the camelina plant was smaller, but in the same range, as in the short-term potential assessment in Karlsson Potter *et al.* (2020). The yield of camelina oil was obtained using an average recovery value of 42.5% from camelina seed to camelina oil on a mass basis.

In the Aspen model (for generating mass and energy balance), the bioconversion plant for forest residues was assumed to process 200 000 dry t forest residues per year, assuming 8 000 hours yearly operating time. The capacity of the MO plant was based on previous studies (Barta *et al*., 2010; Karlsson *et al*., 2016) and annual feedstock use was taken as approximately one-third of the forest residues from the county of Dalarna, assuming clear-cutting of 18 000 hectares and harvest (after considering losses) of approximately 31 t (dry matter) per hectare. Based on an estimated conversion efficiency of 11 % on a mass basis, the corresponding oil supply was derived (21 800 t MO $year^{-1}$) and used as starting point for estimation of annual oil production in both systems (Table 1).

Table 1. Summary of key assumptions applied in the techno-economic analysis.

	Camelina oil	Microbial oil (MO)
Annual production	21 500 t $year^{-1}$	21 800 t $year^{-1}$
Amount of feedstock needs	54 700 t $year^{-1}$	200 000 t DM $year^{-1}$
Base year	2020	2020
Discount rate	6 %	6 %
Plant lifetime	20 years	20 years
Total indirect capital costs (TIC) (startup costs)	5 % of total direct capital costs (TDC)	5 % of TDC
Chemical Engineering Plant Cost Index (CEPCI) ratio	1.10	1.08
Scale factor (SF)	0.6	0.6

The techno-economic assessment comprised high-level estimation of the costs of producing the two types of feedstocks for HVO, *i.e*., camelina oil and MO. This means that transportation to and from the oil-producing plants and HVO production were not included in the detailed assessment. The reasons why only production of HVO feedstocks was considered were because this process has not been investigated as extensively as HVO production and because the cost of feedstock can be a determining factor for the economic viability of the process.

3.2 CLIMATE IMPACT ASSESSMENT

3.2.1 Methodological choices and system boundaries

Life cycle assessment (LCA) was used to assess the climate impact of the two different HVO production pathways. Two different methods based on a LCA approach were used: 1) The method from EU Renewable Energy Directive 2018/2001 (European Parliament, 2018) (RED II), here called the RED II method; and 2) a method following the ISO standards (ISO, 2006b; ISO, 2006a) for LCA, here called the ISO method. The main differences between the two are the methods used to handle multifunctionality and handling of changes in carbon storages in soil organic carbon and aboveground biomass (Figure 6).

The RED II method handles by-products by allocating the climate impact based on energy content of the different products. The ISO method applies system expansion to handle by-products and includes impacts on the primary production system due to residue harvesting, such as soil carbon changes or nitrogen compensation (the latter relevant for the forest residues system).

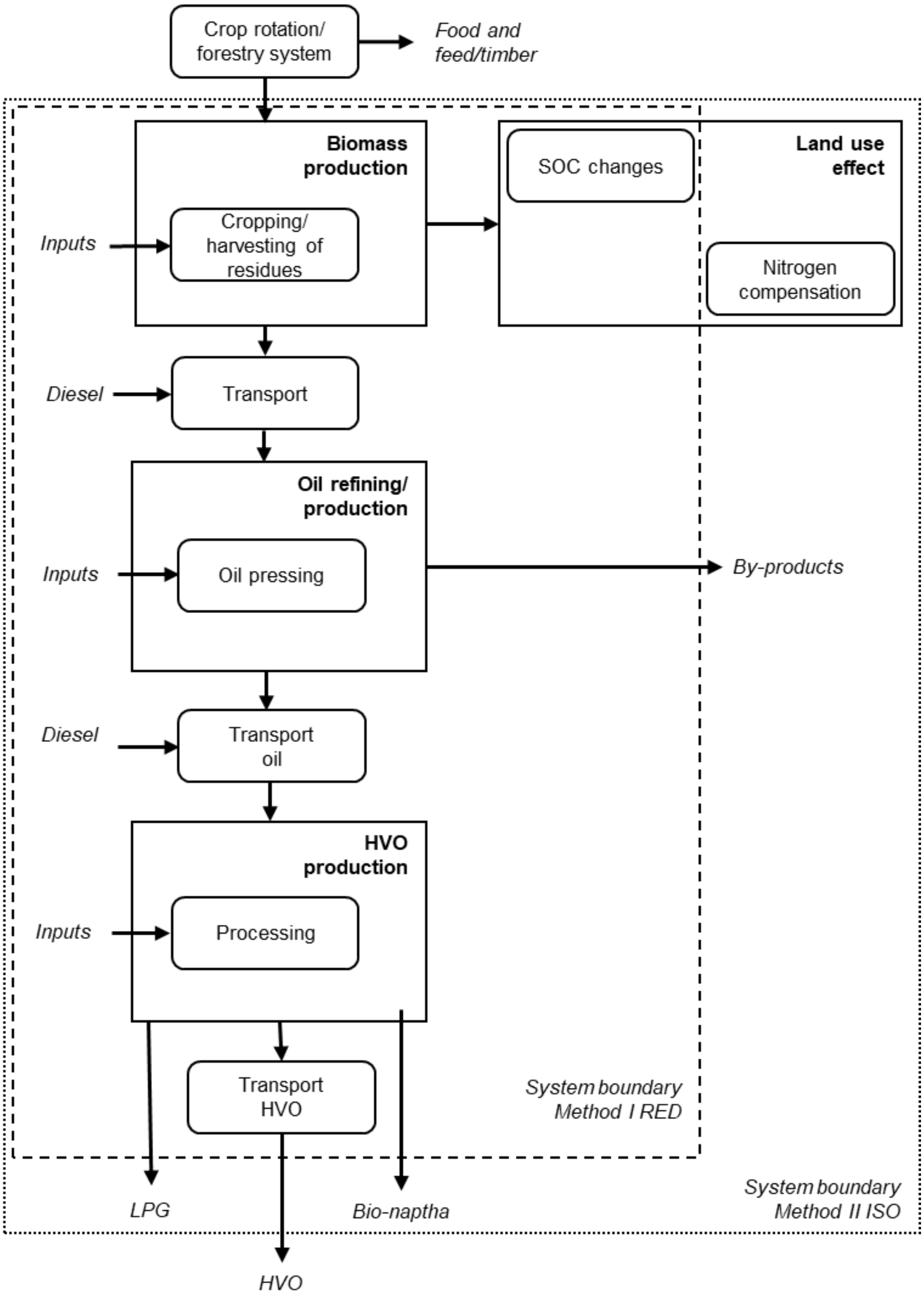


Figure 6. System boundaries applied in the RED II method (Method I) and the ISO method (Method II). SOC=soil organic carbon.

3.2.2 Handling changes in soil organic carbon and aboveground biogenic carbon

Biogenic carbon changes due to direct land use change was included in both scenarios. Both systems affected long-term biogenic carbon stocks. System I (camelina) affected soil organic carbon (SOC) stock in agricultural soil when a cover crop was introduced, compared with a reference with bare soil in the winter. In System II (forest residues), harvesting of forest residues as opposed to leaving them on-site affected aboveground and belowground biogenic carbon storage.

For the RED II calculation we apply the methodology from the Renewable Energy Directive. At the time of writing, the new EU Renewable Energy Directive had yet to be fully implemented in Swedish law. Therefore, handling of changes in SOC and aboveground carbon storage in the RED II method was not officially known, so the way they are handled in this report should be viewed as an interpretation of the EU Directive by the authors.

According to the RED II method, annual emissions from carbon stock changes due to land use change must be included in calculation of GHG emissions. In the camelina system, HVO fuel is produced from cover crops, and RED II states that negative emissions from SOC changes due to improved agricultural management, such as introducing cover crops, must be taken into account if it is reasonable to expect that SOC stocks would increase (European Parliament, 2018). Increasing the biomass input to the soil, as is the case when camelina is used as a cover crop, generally increases SOC stocks (Paustian *et al.*, 2016). However, RED II does not state any preferred approach for accounting for SOC changes due to improved agricultural management (European Parliament, 2018), and we therefore used the same approach for both the RED II method and the ISO method.

In our interpretation, biogenic carbon changes due to forest residue harvesting should not be included in the GHG calculation in the RED II method. From RED II, it appears that changes in biogenic carbon should be included if the change is on cropland, as defined by the International Panel on Climate Change (IPCC) (see Appendix 5, point 7 in RED II) (European Parliament, 2018). For the purpose of allowing comparison with and without inclusion of changes in biogenic carbon stocks, we calculated climate impact with and without biogenic carbon changes for the forest residues system, when using the RED II method. Biogenic carbon changes were included in the ISO method.

Accounting for the climate effect of changes in biogenic carbon stocks, such as stocks in soil due to improved agricultural management, is not as straight-forward as accounting for direct GHG emissions, since biogenic carbon changes are a dynamic process (Brandão *et al.*, 2013). The SOC change after a change in agricultural management is not linear and the process is reversible, meaning that accumulated SOC can be lost if the agricultural management changes again (Kätterer & Andrén, 2001). There is no consensus on the appropriate time horizon to use for assessing the climate impact of agricultural management change on SOC (Goglio *et al.*, 2015) or on aboveground biogenic carbon. Twenty years is used as the default value in the IPCC guidelines for national GHG inventories, but SOC changes are slower in colder climates, which indicates that 100 years may be a more appropriate time horizon in countries like Sweden (Ogle *et al.*, 2019; Goglio *et al.*, 2015). A forest rotation in central Sweden is around 90 years, meaning that it will take up to 90 years from harvest until carbon storage in standing biomass is restored after final felling (in a stand perspective).

In the base case for System I (camelina), we chose to model a reference crop rotation (without camelina) and the new crop rotations (with camelina) for 100 years and attributed the difference in SOC between them in each year to the camelina. In a scenario analysis, a time perspective of 20 years was used. For System II (forest residues), we used a reference with no forest residue harvesting and 90 years as the time perspective, in line with the forestry rotation times in central Sweden. In a scenario analysis, a time perspective of 20 years, in line with IPCC guidelines, was applied.

Indirect land use change is relevant to considered if production of biomass affects production of the main product from the land use (*i.e*., the main crops in the crop rotation in the camelina system and the forestry products in the forest residues system). In the present study, it was assumed that production of the main product was not affected, and therefore indirect land use change was not included.

3.2.3 Climate impact metrics

Because of the impact described above on SOC stocks (System I) and aboveground biogenic carbon and SOC (System II), and the time-dynamic nature of these processes, we used two different climate impact metrics: 1) the well-known and established metric Global Warming Potential with a 100-year perspective (GWP_{100}) with characterization factors for climate impact including climate-carbon feedback from IPCC AR5 (Myhre *et al*., 2013a); and 2) the metric Absolute Global Temperature change Potential (AGTP) (also referred to as temperature response). Both metrics are based on radiative forcing (RF), which is a measure of the radiate balance at the tropopause in W m^{-2}. Greenhouse gases have different abilities to absorb and re-emit long-wave radiation, *i.e*., different radiative efficiencies. In addition, they remain in the atmosphere for different periods when emitted, which means that they have different potential to warm the atmosphere (Myhre *et al.*, 2013b).

The GWP expresses the global warming potential of a greenhouse gas (commonly methane (CH_4) and nitrous oxide (N_2O)) in relation to carbon dioxide (CO_2) for a set time period (commonly 100 years), and thereby converts GHG emissions into CO_2 equivalents (CO_2eq):

$$\mathrm{GWP_x(H)} = \frac{\mathrm{CRF_x(H)}}{\mathrm{CRF_{CO_2}(H)}} \tag{6}$$

where *H* is the time horizon and *CRF* the cumulative radiative forcing of an impulse emission of the specific gas *x* compared with an impulse emission of CO_2 during the same period. The GWP_{100} factor applied in this work for CO_2, biogenic/fossil CH_4, and N_2O was 1, 34/36, and 298 (including climate-carbon feedbacks), respectively (Myhre *et al.*, 2013b).

GWP is the most common climate metric used in LCA and is valuable for comparison with previous studies. However, it has disadvantages by overlooking the timing of GHG fluxes. Therefore, it is advisable to use a second climate metric, *e.g.,* AGTP, which can display more information (Levasseur *et al.*, 2016). The AGTP of each greenhouse gas emitted is described by:

$$\mathrm{AGTP_x(H)} = \int_0^H \mathrm{RF_x(t)R_T(H-t)dt} \tag{7}$$

where *RF* is the radiative forcing and R_T is the temperature impulse response function due to a unit change in RF from a pulse emission of the specific greenhouse gas *x*. The total temperature response is the sum of the AGTP of all GHG emissions (*E*) during the studied time horizon (*H*) (measured in degrees K):

$$\text{Temperature response (H)} = \sum_{x} \int_{0}^{H} E_x(t)\, \text{AGTP}_x(H-t)dt \tag{8}$$

where *t* is the time of emission or uptake and x is the gas (in this work emissions of CO_2, CH_4, and N_2O were considered).

3.2.4 Functional unit and handling of by-products

Functional unit

The functional unit was *1 MJ HVO transported to a gas station in central Sweden*. This functional unit was used because it is representative of the function of HVO, *i.e.*, the energy content of the fuel, and can be compared for equivalent fuels such as fossil diesel or FAME. 1 MJ biofuel is also the functional unit used in EU RED II, which enables comparison with other fuel pathways and to reduction targets.

Handling of by-products – allocation

Several by-products are generated in both System I and System II. In the climate impact calculations, emissions from the HVO process and upstream processes were allocated on the different products based on energy content in the RED II method (Figure 7), as specified in EU RED II. Allocation factors used are presented in Table 2. In System I, camelina meal was co-produced with camelina oil. We assumed that 1.85 kg camelina meal per kg camelina oil was produced (Li & Mupondwa, 2014). Lower heating value (LHV) of camelina oil and camelina meal, as reported by Matteo *et al.* (2020), was used to calculate allocation factors. In System II, biogas and electricity were generated in the biochemical conversion of forest residues. By-products from HVO production were assumed to be propane and naphtha, and allocation factors were calculated using lower heating values (Berkeley Department of Astronomy, year unknown).

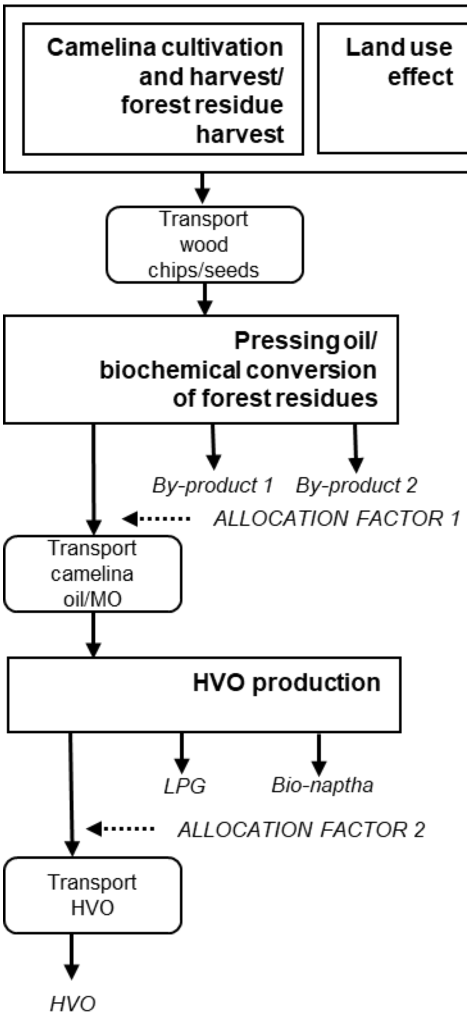


Figure 7. Principles for allocation based on energy content of the hydrotreated vegetable oil (HVO) products in lower heating value (LHV) in the RED II method. By-products 1 and 2 are different for the two systems studied.

Table 2. Allocation factors (energy allocation) used in the RED II method.

	System I: Camelina	System II: Forest residues
Allocation factor 1	46 %	70 %
Allocation factor 2	94 %	94 %

Handling of by-products- substitution

System expansion by substitution was used in the ISO method. The camelina meal obtained as a by-product from oil extraction was assumed to replace soybean meal as animal feed, with 1.71 kg soybean meal replaced for every 1 kg camelina oil produced (Li & Mupondwa, 2014). In the base case, it was assumed that the feedstuff replaced was Brazilian soybean meal. In the time-distributed inventory for the AGTP impact assessment, it was assumed that all substituted emissions from the soybean meal occurred during year 1.

The biogas and electricity produced as by-products from biochemical conversion of forest residues were assumed to replace fossil fuels. The biogas was assumed to replace gasoline in a ratio of 0.98 MJ gasoline MJ^{-1} biogas (Huss *et al.*, 2013), while the electricity was assumed to replace electricity produced from natural gas. In the by-products from the HVO production process, propane was assumed to replace fossil propane (produced from crude oil distillation and processing) and naphtha was assumed to replace gasoline.

The fossil reference was set to 94g CO_2eq, in line with EU RED II (European Parliament, 2018). In the time dynamic assessment, it was assumed that all of these emissions were in the form of CO_2.

4 INVENTORY DATA

4.1 SYSTEM I: HVO PRODUCED FROM *CAMELINA SATIVA* AS A COVER CROP

There are very few published studies on field trials with camelina in Scandinavia, especially as a relay or cover crop. We therefore assumed camelina yield of 1 560 kg ha^{-1} and fertilization requirement of 80 kg N ha^{-1}, based on the average yield and nitrogen (N) fertilizer rate in field trials with relay camelina-soy in North Dakota and Minnesota, USA (Berti *et al.*, 2015; Gesch *et al.*, 2014) and winter camelina in Denmark (Zubr, 1997). Phosphorus (P) and potassium (K) fertilizer rate was set to 15 and 35 kg ha^{-1}, respectively, and pesticide rate was set to 0.76 kg active ingredient ha^{-1}, based on national averages for all crops (Statistics Sweden, 2011). It was assumed that no additional seedbed preparation was needed for cultivating camelina compared with the reference case. Hence, only sowing, applying fertilizer, spraying, and threshing were included. All emissions in the camelina HVO production process were calculated in the same way with both the RED II method and ISO method, except for the handling of by-products (see section 3.2.2).

Since there have been no field experiments with this crop rotation in Sweden, it was not possible to say whether camelina cultivation would affect the yield of the other crops in the rotation. If the yield were to decrease, camelina-based HVO would displace part of food production and would therefore be responsible for any increased environmental impact which producing that amount of displaced crop elsewhere would entail, *e.g.*, clearing land to create new agricultural land. If that were the case, camelina oil would probably not be classified as a fuel with low indirect land-use change risk according to the EU RED II Directive. In this study, we assumed the camelina would not affect the yield of the other crops. However, testing the crop rotation in practice would be necessary to confirm that assumption.

4.1.1 Crop production system

The seed used for sowing was accounted for by subtracting 7 kg ha^{-1} from the yield (Berti *et al.*, 2015). Fertilizers were assumed to be applied as calcium ammonium nitrate (N), triple superphosphate (P), and potassium chloride (K). The emissions inventory for producing these was taken from the GaBi database (Fertilizers Europe, 2018a; Fertilizers Europe, 2018c; Fertilizers Europe, 2018b; Brentrup *et al.*, 2016), which is representative of mineral fertilizers produced in Europe. Emissions associated with pesticide production were taken from the ecoinvent database v 3.7 (Wernet *et al.*, 2016). Direct and indirect soil N_2O emissions were calculated using the IPCC Tier 1 guidelines with the site-generic emission factors (Hergoualc'h *et al.*, 2019). Fuel consumption during field operations was calculated according to Lindgren *et al.* (2002) and emissions from fuel production and combustion using data from Gode *et al.* (2011b).

Table 3. Names of ecoinvent processes used for inventory data in this study. All inventories were taken from ecoinvent version 3.7. 'Allocation, cut-off by classification' was used for all data except for soybean meal, where 'Substitution, consequential, long-term' was used.

ecoinvent process name	Used in this study for:
Market for pesticide, unspecified, GLO	Pesticide production emissions
Market for hexane, GLO	Camelina oil extraction
Market for heat, district or industrial, natural gas, Europe without Switzerland	Camelina oil extraction
Electricity, high voltage, production mix, SE	Camelina oil extraction
Market for transport, freight, lorry, unspecified, RER	Transport of camelina seed to extraction facility and camelina oil to HVO plant
Soybean meal and crude oil production, BR	Substitution by camelina meal
Soybean meal and crude oil production, US	Alternative substitution by camelina meal

4.1.2 SOC changes

The regional version of the Introductory Carbon Balance Model (ICBM) (Andrén *et al.*, 2004; Andrén & Kätterer, 1997) was used to assess SOC changes. ICBM is a two-compartment process model based on first-order kinetics which can be used to calculate SOC changes in the top 25 cm of agricultural soil. We chose the parameters k_y, k_o, and h from Andrén and Kätterer (1997) and the site-dependent factor r_e from Andrén *et al.* (2008). Yields of crops in the rotation (other than camelina) were based on official statistics on average yield in each cultivation zone in Sweden between 2010 and 2019 (Statistics Sweden, 2020). The amounts of crop residues were calculated based on the yields according to the equations provided by Andrén *et al.* (2004) for spring barley, winter wheat, and camelina, and for peas based on data provided by Hergoualc'h *et al.* (2019). It was assumed that all crop residues had a carbon content of 0.45 kg kg^{-1} DM and that all residues were left in the field. The initial SOC content of the soil was set by running ICBM for the reference crop rotation until approximate SOC equilibrium (difference in mean SOC content between two cropping cycles less than 0.000001 kg C ha^{-1}).

4.1.3 Camelina oil extraction and refining

Data from Li and Mupondwa (2014) were used for assessing the electricity, heat, and hexane required for extraction of oil from the camelina seeds. The inventories used for each input were taken from ecoinvent v 3.7 (Table 3).

4.1.4 Transport and distribution

The camelina seeds were assumed to be transported 100 km to the oil extraction plant, and the camelina oil produced was assumed to be transported 200 km to the HVO processing plant. The inventories used for the transport was taken from ecoinvent v 3.7 (Table 3).

4.1.5 Scenario analysis

There are substantial uncertainties about how the camelina cultivation would perform in Sweden and methodological choices that could influence the results of the camelina HVO. We therefore selected five variables to include in scenario analysis. These were:

- Yield (+/-20%). It is possible that camelina cultivation would work better or worse in Sweden than the assumed yield. In addition, crop breeding may be able to increase the yield in the future.
- Nitrogen fertilizer amount (+/-20 %). It is possible that camelina cultivated in Sweden would require a different amount of fertilizer than assumed in the base case, and that future crop breeding can improve fertilizer uptake.
- Other emission factor for soil N_2O emissions. Previous assessments of biofuels according to the RED calculation guidelines have most often used a site-generic version of the IPCC guidelines for calculating soil N_2O emissions (De Klein *et al.*, 2006), which we also did in the base case. Since 2019, there are updated IPCC guidelines that provide the opportunity to differentiate between wet and dry climate. In a scenario analysis, we tested the outcome of using the emission factors for a wet climate instead.
- Other time horizon for SOC changes. As previously mentioned, the choice of a 100-year time horizon is somewhat arbitrary. In a scenario analysis, we applied a 20-year perspective instead.
- Other substituted soybean meal. In the base case, camelina meal was assumed to replace Brazilian soy. However, Europe also imports almost as much soy from the US as from Brazil (Gale *et al.*, 2019), so in a scenario analysis we tested the influence on the results if the camelina meal replaced US soybean meal instead of Brazilian (Table 3).

We only present the results for the scenarios using the GWP impact assessment.

4.1.6 Techno-economic analysis of camelina oil

The reference CAPEX and percentage OPEX for camelina oil production were taken from Mupondwa *et al*. (2016). The key values used for adjusting the cost and revenues to those assumed in the camelina system are presented in Table 4, with the costs converted from 2016 to 2020 currency rate. The annual production of the camelina oil was assumed to be 21 500 t year^{-1} as presented earlier (Table 1).

Table 4. Reference data used in the techno-economic assessment of camelina oil.

	Value	Unit
Capital expenditure (CAPEX)[1]	171	MSEK
Percentage operating costs (OPEX)[1]	137	%
Price of camelina seeds[a]	2.70	SEK kg^{-1} seeds
Reference input capacity[a]	250 000	t year^{-1}
Reference output capacity[a]	107 000 000	l year^{-1}
Price of camelina meal[b]	3.54	SEK kg^{-1} meal

[a]upondwa *et al*. (2016), [b]Markets insider (2021).

4.2 SYSTEM II: HVO PRODUCED FROM FOREST RESIDUES (TOPS AND BRANCHES) USING OLEAGINOUS YEAST

4.2.1 Forest residue harvesting

Forest residues (tops and branches) harvested after final felling from a theoretical forest stand in central Sweden (Dalarna) were studied. The forest residues were assumed to be forwarded to the roadside for eight months of storage, after which the residues were chipped and transported to the biochemical conversion plant. Emissions from transport of machinery and ash recycling by a converted forwarder were also included in the assessment (assuming the same transport distance as for the wood chips) (Table 5). In the ISO method, nitrogen fertilization to compensate for removed nitrogen was included.

Table 5. Inventory data for forest residues (h_{15} includes pauses shorter than 15 min, DM = dry matter).

	Value	Unit
Forwarding		
Diesel use	10.8[a]	L h_{15}^{-1}
Time	8.4[b]	minutes Mg^{-1} DM
Chipping		
Diesel use	3.05[c]	L Mg^{-1} DM
Losses	3.6[d]	%
Transport wood chips		
Load	34	Mg
Diesel use	0.58[e]	L km^{-1}
Distance (one-way)	60.2[f]	km
Distance (total)	111.5[e]	km
Lubrication oil	20	% of diesel use
Ash recycling		
Amount	2[g]	Mg ha^{-1}
Loading time	0.8[h]	minutes Mg ash^{-1}
Spreading time	3.3[h]	minutes Mg ash^{-1}
Diesel use	10.8	h_{15}^{-1}

[a]Brunberg (2013), [b]Eliasson and Lundström (2013), [c]Eliasson *et al.* (2012), [d]Lindholm *et al.* (2010), [e]Full loading rate 54% of the distance based on Andersson and Frisk (2013), [f]Asmoarp *et al.* (2018), [g]Swedish Forest Agency (2008), [h]Magnusson and Lindblad (2013).

4.2.2 Land use change and biogenic carbon fluxes

The theoretical forest stand was assumed to be located in central Sweden (Dalarna, with a forest rotation period of 90 years), based on Hammar *et al.* (2015). The Heureka system coupled with the decomposition model Q (Wikstrom *et al.*, 2011) was used for simulating biomass growth and biogenic carbon fluxes from harvesting forest residues. No impact on future forest productivity as a consequence of removing forest residues was considered, but nutrient compensation for nitrogen removal was considered in the ISO method. Nutrient compensation was not included in the RED II method. Although it is not explicitly explained in EU RED II that this should be included, it states that GHG emissions associated with "extraction or cultivation process itself" should be accounted for (European Parliament, 2018). However, nutrient compensation is more of an indirect effect and was therefore not considered here when using the RED II method.

The net land use effect was calculated as the yearly difference between harvesting forest residues, which releases CO_2 during the same year, and leaving the forest residues at the forest site, which partly releases the CO_2 over time due to decomposition.

4.2.3 Biomass properties

The lower heating value (LHV) of the wood chips was calculated based on the higher heating value (HHV) adjusted for the moisture content (MC) and ash content (AC) (Table 6):

$$LHV_{MC} = (HHV - 2.45 \cdot 0.09 \cdot H_2) \cdot \left(1 - \frac{AC}{100}\right) - 2.45 \cdot \frac{MC}{100 - MC} \qquad (9)$$

where LHV_{MC} is the theoretical heat gain from wood chips excluding water condensation heat, 2.45 is the latent heat of water vaporization at 20°C (MJ kg^{-1}), 0.09 represents one part hydrogen and eight parts oxygen in water, and H_2 is the hydrogen content (6 % assumed) (Lehtikangas, 1999).

Table 6. Biomass properties (DM = dry matter).

	Value	Units
Harvest tops and branches	35.3[a]	Mg DM ha^{-1}
Higher heating value (HHV)	20.8[b]	MJ kg^{-1} DM, ash free
Moisture content (MC)	45[c]	%, wet basis
Ash content (AC)	1.5	%, dry basis
Lower heating value (LHV_{MC})	17.2	MJ kg^{-1} DM, dry basis

[a]Hammar *et al.* (2015), [b]Nilsson *et al.* (2012), [c]50% for fresh biomass, lowered after storage based on Strömberg and Herstad Svärd (2012) and Paulrud *et al.* (2010).

4.2.4 The biochemical conversion plant

For the climate impact assessment on System II, it was assumed that the bioconversion plant was located in central Sweden and processed 200 000 dry t forest residues $year^{-1}$, and 25 t $hour^{-1}$ assuming 8000 hours yearly operating time, and that yearly production of MO was 21 800 $tyear^{-1}$ or 332 GWh $year^{-1}$. Mass and energy balances of the biochemical conversion plant were modeled using the software Aspen Plus™ V11. Electricity demand and heat and cooling requirements for the different processes within the MO plant are listed in Appendix 1 to this report. Burning the lignin in a CHP satisfied the energy demand for MO production and some surplus electricity was available for sale on the market.

The forest residues bioconversion process consists of the following steps: i) pretreatment of the biomass to hydrolyze some of the sugars and make the biomass more susceptible to enzymatic hydrolysis; ii) enzymatic hydrolysis, using enzymes to hydrolyze especially the hexose sugars in the cellulose, iii) fermentation, where the sugars are converted to lipids using oleaginous yeast, and iv) MO extraction using hexane. The remaining biomass after MO extraction and waste streams from other processes are anaerobically digested to produce biogas, followed by wastewater treatment to enable circulation of some of the water. All steps are further explained below.

In this study, pretreatment was assumed to be performed using steam explosion (210°C and 2.5% sulfuric acid (SO_2)) followed by enzymatic hydrolysis. The biomass composition was assumed to be 43.5 % glucan, 12.8 % mannan, 2.1 % galactan, 5.1 % xylan, 1.5 % arabinan, and 29.4 % lignin (Barta *et al.*, 2010). During steam explosion, conversion of the cellulose fraction was assumed to be 16.1 % and that of the hemicellulose fraction 67.4 % (Barta *et al.*, 2010). Generation of degradation products was assumed to be 2.2 % of the hemicellulose fraction and 1.3 % of the cellulose fraction. After steam explosion, there is still non-hydrolyzed material present. This material was assumed to be treated further with enzymatic hydrolysis (residence time 48 h in a batch process) and the conversion rate in this step was assumed to be 90 %. The enzyme dose was assumed to be 16 g kg^{-1} DM forest residues (Table 7).

The yeast *Rhodotorula toruloides* was assumed to be used, as this yeast has been proven to grow well on hydrolysate from forest residues in the laboratory, with around 70 % fat content at the end of fermentation (unpublished results; Volkmar Passoth, personal communication 12 May 2021). In the present study, a fat content of 65 % of total cell mass was assumed after the MO accumulation step. A 65 % MO content in the cells corresponded to a MO yield of 0.24 g MO g^{-1} sugar or 0.12 kg MO kg^{-1} DM forest residues before extraction of the oil.

Yeast propagation and MO accumulation are carried out in two steps, both during aerobic fermentation in fed-batch reactors. Nitrogen is supplied in the yeast propagation step, while the MO fermentation takes place without nitrogen being added. We assumed a residence time of 2 days for yeast propagation and 4 days for MO accumulation, and a temperature of 25°C in both reactors. Energy demand for agitation and aeration was assumed to be 0.61 kw m^{-3} active volume (Hensirisak *et al.*, 2002). The yeast cells in solution were assumed to be filtered to 30 % solids using a rotary drum filter, after which the biomass was heated to 65°C in order to deactivate the enzymes in the yeast cells. The yeast cells were then assumed to be homogenized and the MO extracted using hexane (20 % w/w yeast in hexane). The hexane was assumed to be recycled later with approximately 0.5 % losses (Davis *et al.*, 2014). Here, 10 % of the MO was assumed to remain with the yeast biomass after extraction, which was fed to the biogas reactor (Karlsson *et al.*, 2016). There are many different methods that could be applied for oil extraction, but using hexane was considered to be most feasible in the near-term technological development (Volkmar Passoth, personal communication 18 March 2021).

Biogas production from the yeast biomass, the remaining MO after the extraction, and wastewater treatment was modeled as in Karlsson *et al.* (2016). The resulting biogas was assumed to be upgraded using a water scrubber, which was modeled in accordance with Cozma *et al.* (2013).

Wastewater treatment (aerobic treatment) and water recycling were modeled based on Humbrid *et al.* (2011).

Table 7. Inputs and products of the biochemical conversion process based on 1 kg dry matter (DM) forest residues and assuming a plant with capacity for processing 200 000 t DM forest residues annually.

Inputs		Units	Yearly values	Units
Biomass	1.000	kg DM	200 000	t DM yr^{-1}
Sulfuric acid	0.025	Kg kg DM^{-1}	5 000	t yr^{-1}
Enzymes	0.016	kg kg DM^{-1}	3 180	t yr^{-1}
Ammonia	0.008	kg kg DM^{-1}	1 610	t yr^{-1}
Hexane	0.005	kg kg DM^{-1}	1 010	t yr^{-1}
Methane slip	0.11	g kg DM^{-1}		
NaOH	0.33	g kg DM^{-1}	65.2	t yr^{-1}
H_3PO_4	0.11	g kg DM^{-1}	21.8	t yr^{-1}
Products				
Microbial oil	0.109	kg kg DM^{-1}	21 800	t yr^{-1}
Biogas	0.029	kg kg DM^{-1}	5 820	t yr^{-1}
Electricity	0.232	kWh kg DM^{-1}	46.4	GWh

Inventory data for inputs to the biochemical conversion process were gathered from different literature sources, mainly ecoinvent (Wernet *et al.*, 2016) (Table 8). Data for enzymes were obtained from Novozymes (Jesper Kløverpris, personal communication 19 April 2016).

Table 8. Names of ecoinvent processes used for inventory data for System II: Forest residues. All inventories were taken from ecoinvent version 3.7. 'Allocation, cut-off by classification'.

ecoinvent process name	Used in this study for:
Market for inorganic nitrogen fertilizer, as N, SE	Nitrogen in yeast propagation
Market for sulfuric acid, RER	Acid in pre-treatment of forest residues
Market for hexane, GLO	Microbial oil (MO) extraction
Market for sodium hydroxide, without water, in 50 % solution state, GLO	MO purification
Market for phosphoric acid, fertilizer grade, without water, in 70 % solution state, RoW	MO purification
Market for transport, freight, lorry, unspecified, RER	Transport of MO and HVO

4.2.5 Scenario analysis

Production of HVO from forest residues using oleaginous yeast is not yet a large-scale industrial process and there are several uncertainties related to the conversion process, especially the biochemical conversion of sugars to MO and MO extraction from the yeast cells. Hydrolyzing the lignocellulosic biomass (forest residues in this case) can be considered to be a more established process since this is also part of lingo cellulosic ethanol production. Further, there are methodological challenges related to how to handle changes in biogenic carbon stocks, which can have a considerable impact on the results. We performed a number of scenario analyses on the following aspects of the process:

- MO yield (+/-20 %) (in the base case 65 % MO content in the cells was assumed after fermentation). Yeast strains are being refined to grow better and faster on different substrates. Therefore, the MO yield was varied in one scenario analysis.

- MO extraction. After MO accumulation, the MO is extracted from the yeast cells, which can be done at different levels of efficiency. The effects of 5 % and 15 % losses were analyzed here.
- Other time horizon for biogenic carbon changes. As previously mentioned, the choice of a 90-year time horizon is somewhat arbitrary. In this scenario analysis we applied a 20-year perspective instead.

We only present the results for the scenarios using the GWP impact assessment.

4.2.6 Techno-economic analysis of MO

For System II, the literature values for CAPEX were obtained from Koutinas *et al.* (2014) and Olofsson *et al.* (2017). Different sources were needed because the cost of the whole MO production process from forest residues using oleaginous yeast was not available in a single publication. Data from Olofsson *et al.* (2017) were used for the pretreatment and hydrolysis steps, while data from Koutinas *et al.* (2014) were used for MO production and extraction. The costs for other steps, such as separation and MO accumulation, were assumed to be negligible.

Since the MO processes was assumed to have an integrated CHP and biogas plant to produce electricity and biogas as by-products, CAPEX for these were also included. The CAPEX value for the CHP was taken from Olofsson *et al.* (2017), as the capacity of the plant was similar to that assumed in the present case. The CAPEX value for the biogas plant was obtained from a study by Barta *et al.* (2010), which provides total direct cost of anaerobic digestion (AD) and upgrading of the biogas. Barta *et al.* (2010) also assessed the costs for different scenarios, where the level of chemical oxygen demand (COD) was one of the parameters. Their scenario that had the most similar COD level (Scenario A4) was chosen as the reference in this study. The capacity of the MO plant was calculated assuming a forest residue input of 200,000 t DM year^{-1}

The key values used to adjust the cost and revenues are presented in Table 9. As mentioned, OPEX for MO production was assumed to be dominated by the cost of material used. The materials consumed and their prices are shown in detail in Appendix 1.

Table 9. Reference data used in the techno-economic assessment of microbial oil (MO).

	Value	Unit
CAPEX – pretreatment[a]	134	MSEK
CAPEX – Hydrolysis[a]	103	MSEK
CAPEX – MO production[b]	554	MSEK
CAPEX – MO extraction[b]	10	MSEK
CAPEX – CHP[a]	33	MSEK
CAPEX – Biogas plant[c]	78	MSEK
Reference input capacity[a]	21 900	t forest residues year^{-1}
Reference output capacity[a]	24 000	t MO year^{-1}
Price of forest residue[d]	895	SEK t dm^{-1}
Price of electricity (without tax)[e]	0.36	SEK kWh^{-1}
Price of biogas (without 25% vat)[f]	15	SEK kg^{-1}

[a]Olofsson et al. (2017), [b]Koutinas et al. (2014), [c]Barta et al. (2010), [d]Energimyndigheten (2020), [e]Eurostat (2020), [f]Svensk Biogas (2021).

4.3 CONVERSION TO HVO FROM CAMELINA OIL AND MO

The process for hydrotreating the oil was modelled similarly for camelina oil and MO. Process data were gathered from the literature and primary data from Preem and Neste (Table 10). Vegetable oil was assumed to be converted to HVO to 86.4 % w/w for camelina oil and 85.4 % w/w for MO (Katarina Persson, Preem, personal communications May-June 2021). For 1 kg untreated oil, the input to the process was assumed to be 37 g of hydrogen for camelina oil and 32 g hydrogen for MO (*ibid*.). The hydrogen was assumed to be generated using natural gas (Pekka Nurmi, Neste, personal communication 12 May 2021). Input of electricity was assumed to be 0.09 MJ kg oil^{-1} electricity (ibid.), which in this study was assumed to be produced from natural gas, although that might differ between different plants. All heat required in the process was assumed to be generated internally (*ibid*.). By-products generated in the HVO process were assumed to be propane and naphtha (*ibid*.). The propane was assumed to be partly sold and partly used internally (based on the Neste Rotterdam plant). For every kg HVO produced, it was assumed that 35 g of propane could be sold of around 49-72 g propane generated (data from Neste, Preem, and Nikander (2008)). Naphtha was assumed to be generated in smaller quantities, approximately 25 g kg^{-1} HVO produced (Nikander, 2008). Transport of the HVO 300 km from Gothenburg to central Sweden (Hjortkvarn, demographic center of Sweden) was included. Inventory data were taken from ecoinvent version 3.7 (Wernet *et al.*, 2016) (Table 19), except for natural gas electricity, for which inventory data were taken from Gode *et al.* (2011a).

Table 10. Inputs and outputs in the hydrotreated vegetable oil (HVO) production process.

	Camelina oil	Microbial oil	Units
Inputs			
H2	37	32	g
Electricity	0.09	0.09	MJ
Oil	1	1	kg
Heat[a]			
Outputs			
HVO	0.864	0.854	kg
Naphta	25	25	g
Propane	35	35	g

[a]Assumed to be produced from propane, surplus assumed to be sold (output below is surplus)

Table 11. Names of ecoinvent processes used for inventory data for hydrotreated vegetable oil (HVO) production in this study (used in both System I and System II). All inventories were taken from ecoinvent version 3.7. 'Allocation, cut-off by classification'.

ecoinvent process name	Used in this study for:
Hydrogen production, gaseous, petroleum refinery operation, Europe without Switzerland	HVO production
Propane extraction, from liquefied petroleum gas, GLO	Alternative production of propane

5 RESULTS AND DISCUSSION

This chapter presents and discusses results from the techno-economic assessment (section 5.1) and the climate impact assessment (section 5.2). Environmental aspects other than climate effects are discussed in section 5.3. General aspects of both systems analyzed are discussed in section 5.4.

5.1 TECHNO-ECONOMIC ASSESSMENT

In this study, techno-economic analysis was performed on camelina oil and MO production from forest residues, with the two oils then used as feedstock for HVO production. The outcome of the analysis was the cost of camelina oil and MO based on the assumed feedstock cost and oil production capacity and the annual cost of production, when considering the revenues from selling by-products. The results are presented in the following sub-sections. The cost of oil can be used as an indicator of the relative production cost difference of the two included HVO production pathways using two different types of feedstocks.

5.1.1 System I: HVO produced from *Camelina sativa* as a cover crop

The results from the techno-economic analysis of camelina oil production, including annual CAPEX, OPEX, assumed feedstock cost, revenue from the sale of by-products and the corresponding estimated cost of oil, are shown in Table 12. The price of camelina oil was estimated to be 5.01 SEK L^{-1}.

Table 12. Results of techno-economic analysis of camelina oil production including annual CAPEX, OPEX, assumed feedstock cost and revenue from the sale of by-products and finally the corresponding estimated cost of oil. For references used see Section 3.1.

	Value	Units
Annual CAPEX	7	MSEK $year^{-1}$
Annual OPEX excl. feedstock cost	104	MSEK $year^{-1}$
Annual feedstock cost	148	MSEK $year^{-1}$
Revenue from by-product	141	MSEK $year^{-1}$
Annual cost	117	MSEK $year^{-1}$
Oil production capacity	23 400 000	L $year^{-1}$
Cost of oil	**5.01**	**SEK L^{-1}**

As Table 12 shows, CAPEX in production of camelina oil was considerably lower than OPEX (feedstock cost excluded). On the contrary, camelina oil production cost was heavily dependent on feedstock prices. However, the cost of feedstock was compensated for to a substantial degree by the revenues from selling the camelina meal (estimated to correspond to 95 % of the annual feedstock cost). Considering the revenues from camelina meal, the annual cost of oil production was estimated to be 117 MSEK $year^{-1}$, which resulted in a low price for camelina oil (5.01 SEK L^{-1})

(Table 12). This can be compared to 258 MSEK year^{-1} and an oil price of 11 SEK L^{-1} when revenues from by-products were not considered.

5.1.2 System II: HVO produced from forest residues using oleaginous yeast

The results from the techno-economic analysis of MO production, including annual CAPEX, OPEX, assumed feedstock cost, revenue from the sale of by-products and the corresponding estimated cost of oil, are shown in Table 13. The price of MO was estimated to be 9.60 SEK L^{-1}. For comparison, the cost of MO was estimated at 14 SEK L^{-1} when excluding the revenue from by-products (which were very important for the cost of the oil). The average 2021 price for rapeseed oil is at 11 SEK L^{-1} although lower values have been reported previously (Neste 2021).

Table 13. Results of techno-economic analysis of microbial oil (MO) production including annual CAPEX, OPEX, assumed feedstock cost, revenue from the sale of by-products and the corresponding estimated cost of MO. For references used see Section 3.1.

	Value	Units
Annual CAPEX	113	MSEK year^{-1}
Annual OPEX excl. feedstock costs	39	MSEK year^{-1}
Annual feedstock costs	179	MSEK year^{-1}
Revenue from by-products	104	MSEK year^{-1}
Annual cost	228	MSEK year^{-1}
Oil production capacity	23 700 000	L year^{-1}
Cost of oil	**9.60**	**SEK L^{-1}**

In the case of MO production, the relationship between CAPEX and OPEX (not including the feedstock cost) was the opposite to that found for camelina oil, *i.e.*, CAPEX for MO was greater than OPEX (see Table 13). This was because the MO process produced lignin as a residue that was incinerated in a CHP. The electricity produced was assumed to supply the whole process, thus the cost of electricity was avoided in the OPEX. The cost of feedstock for MO was significantly greater than CAPEX and OPEX (excluding feedstock cost), meaning that feedstock cost was the dominant cost in MO production, as also found in camelina oil production. The price of forest residues in Sweden is relatively low but, due to the low conversion rate of forest residues to MO, large amounts of feedstock are needed in MO production.

Taking into consideration the revenues from selling the excess electricity and biogas, the annual cost of MO production decreased to 228 MSEK, resulting in a cost for MO of 9.60 SEK L^{-1}.

Based on the techno-economic analysis, the cost of MO was higher than the cost of camelina oil (almost twofold higher). This was mainly because the feedstock cost, which was dominant in both production systems, was higher in the case of the MO due to the lower conversion rate, so a greater amount of feedstock was needed for production. CAPEX of the MO plant was significantly higher than CAPEX of the camelina oil plant but, as the MO plant generated its own electricity, OPEX of the MO process was lower. This meant that CAPEX plus OPEX was fairly similar for camelina oil and MO.

The revenues from selling by-products in each process contributed to lower annual cost, which then resulted in lower oil cost. The revenues in the case of camelina oil covered most of the feedstock cost, while in the case of MO the revenues were high, but still lower than the cost of feedstock (representing about 60 %).

In previous studies, the cost of camelina oil was estimated to range from 2.38 to 5.46 SEK L^{-1} (Natelson *et al.*, 2015; Miller & Kuma, 2014). These estimates are in the same range as that in this study, supporting our conclusions. However, as similar work in this area is lacking today, a detailed comparison was not possible.

Several previous studies have assessed the techno-economic potential of MO production from different feedstocks (Koutinas *et al.*, 2014; Bonatsos *et al.*, 2020; Parsons *et al.*, 2019; Braunwald *et al.*, 2016). The selling price of the MO in those studies ranged from 2.4 to 4.1 USD kg^{-1} MO, corresponding to 23-41 SEK L^{-1} MO (assuming a density of 0.92 kg L^{-1}). Great variations among the estimated prices reported can be observed. In most of those studies, the estimated minimum selling price of MO was higher, and in some cases much higher, than the price of vegetable oils, because of different conditions and assumptions in the underlying processes considered. For example, Koutinas *et al.* (2014) and Bonatsos *et al.* (2020) used glucose as the carbon source and assumed a feedstock cost at 400 USD t^{-1} (corresponding to about 3,500 SEK t^{-1} which can be compared to the feedstock cost for forest residues used in this study at 895 SEK t dm^{-1}. The processes described in Koutinas *et al.* (2014) also required intensive use of electricity for drying the yeast and for agitation in fermenters. Moreover, they included the cost of purchasing electricity, instead of having a CHP as in the present case. Braunwald *et al.* (2016) found the lowest estimated price of MO because they used lignocellulosic biomass as a source of sugar, which is cheaper and more similar to our case.

However, as factors such as oil capacity, lipid content, biomass yield, and other costs differ between studies, the estimated prices of MO cannot be directly compared. Costs for removing potential contaminants or for reaching a certain quality level can also be added. Finally, the revenues from selling biomass were considered in this study, which is not the case in the other studies, resulting in large differences in the price of MO.

The cost for vegetable oils used for HVO production, however, seem to vary significantly depending on the type of feedstock used. For rapeseed oil the cost can be up to 15 SEK $L^{-1.}$ (Neste, 2021) while tall oil or other waste baste vegetable oil are in the range of 7-11 SEK L^{-1} (Greenea, 2021, Furusjö & Lundgren, 2017). This of course has an impact on the final HVO price. Based on the results from the recently published KNOGA project a total cost or 8.3 SEK L^{-1} can be expected for HVO produced from tall oil (Holmgren *et* al 2021). Values at the same range had been previously reported by Furusjö & Lundgren (2017) i.e. from 6 to 10 SEK L^{-1} based on various feedstocks. Compared to the values obtained in this study, HVO that would be produced from camelina could result in similar or lower levels while HVO from forest residues can be expected to be somewhat more expensive. The final cost, however, would depend on the underlying conditions but also production capacity.

5.1.3 Sensitivity analysis of economic parameters

To investigate how the cost of oil depend on the input parameters and assumptions used in this work, a sensitivity analysis was performed. The variables that can be expected to affect the cost of oil considerably include: the unit price of feedstock, oil production capacity, OPEX excluding feedstock costs, and the price of by-products. In the sensitivity assessment the value of the variables was varied in the range -50 % to +100 %.

The results of the sensitivity assessment are presented in Figure 8 for camelina oil and Figure 9 for MO.

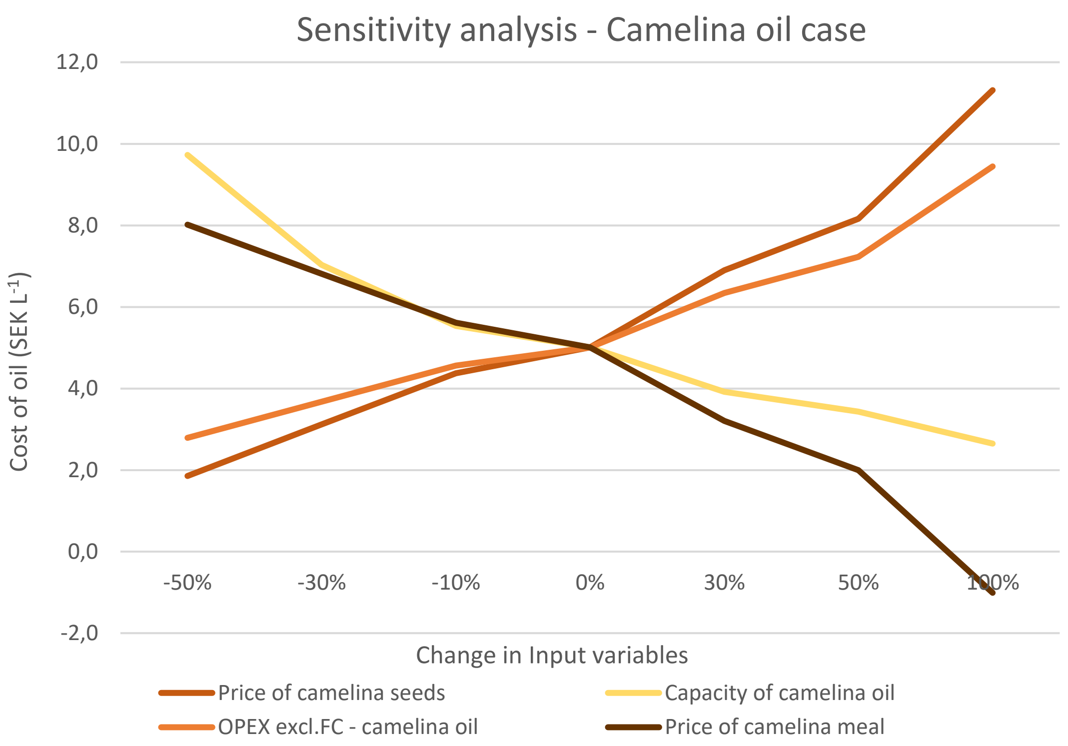


Figure 8. Results of sensitivity analysis of the cost of camelina oil against different input values of the input variables ranging from -50% to + 100% of the value used in the base case estimate.

The cost of camelina oil was sensitive to a change in the price of camelina seeds. When the price was increased by 30 %, the cost of oil increased to almost 7 SEK L^{-1}, (a 40 % increase) (Figure 8). The price of camelina seeds was directly related to the feedstock cost, which was found to be the main contributor to the cost of production, and hence it had a strong effect on the final cost of camelina oil.

Another variable whose value highly influences the oil cost is the price at which camelina meal can be sold on the market. The sensitivity analysis showed that when camelina meal was less attractive on the market (price reduction of 10 %), the cost of oil increased to 6 SEK L^{-1} (+12 %). When the market price of camelina meal was lowered by 50 %, the cost of oil was 8 SEK L^{-1}, which corresponded to a 60 % increase.

The cost of camelina oil also increased when smaller capacity was assumed and decreased when the capacity was larger (Figure 8). The annual capacity for camelina oil production was related to the amount of camelina seeds that needed to be purchased, which in turn caused higher feedstock cost but also higher revenue as more camelina meal was produced. However, the cost of oil was affected more when production capacity was small. OPEX (excl. feedstock cost) had the lowest impact on the cost of oil of all variables tested in sensitivity analysis which is due to that it represents a smaller share of the total cost. However, higher OPEX gives higher oil cost.

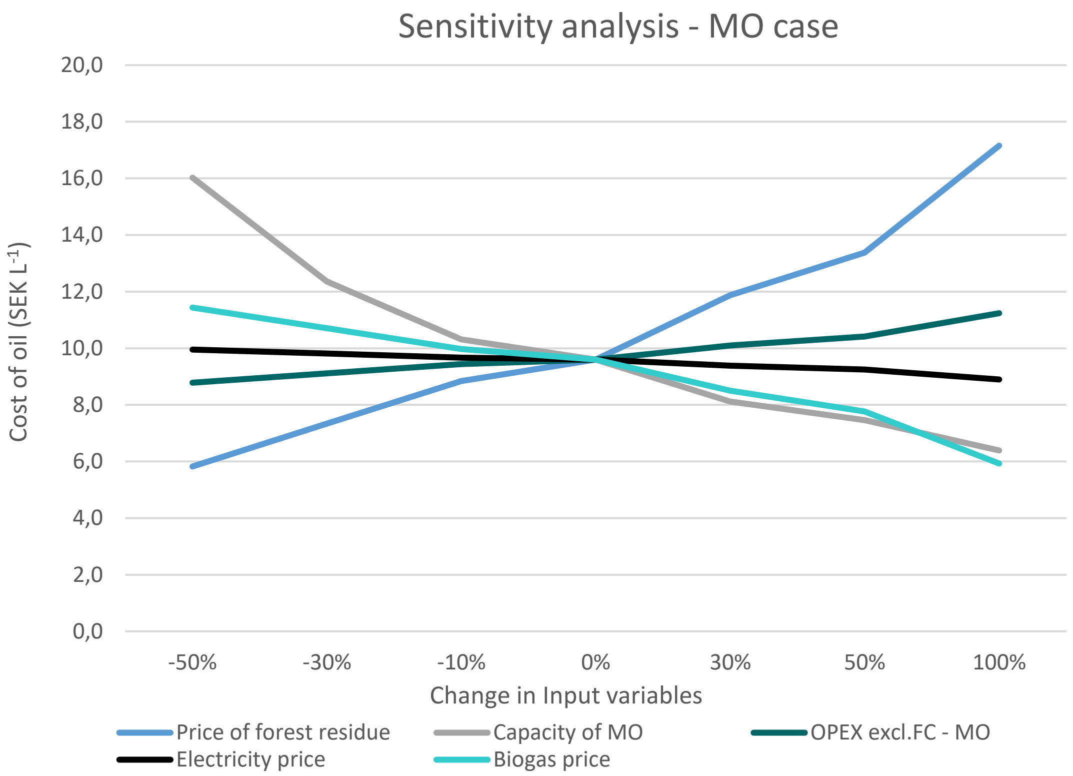


Figure 9. Results of sensitivity analysis of the cost of microbial oil (MO) against different input values of the input variables ranging from -50% to + 100% of the value used in the base case estimate.

The cost of MO seemed to be mostly affected by the cost of feedstock (forest residues and plant capacity) (Figure 9). The higher the price of forest residues, the higher the cost of the oil. The same reasoning as in the camelina oil case applied; since the feedstock price was the dominant cost in the techno-economic model, changes in that had a strong influence on the total cost. A 30 % increase in feedstock price (due to *e.g.*, increased transport distance or increased market demand and competition) would lead to a MO cost of 12 SEK L^{-1} (*i.e.*, 25 % higher). The MO capacity also seemed to affect the oil price, in a similar manner as in the case of camelina. Lower capacity led to higher MO prices, as shown also in Figure 9.

OPEX excluding feedstock cost, biogas and electricity price showed low and approximately similar impact on the final cost of oil (Figure 9). Biogas resulted in slightly higher variations than electricity, mainly because electricity provided a lower share of revenue than biogas (16 % of the total revenues corresponded to electricity).

In summary, the cost of camelina oil showed higher sensitivity to the underlying assumptions that the cost of MO. The cost of oil in both cases was shown to be dependent on the price of feedstock and the revenues from *e.g.*, prices for by-products and production capacity. These parameters are likely to vary depending on demand on the market and the influence of regulations. For example, there is increasing demand for forest residues within the transport sector, as this is more beneficial in terms of the EU Renewable Energy Directive, raising the price of forest residues. The price of the camelina meal is also uncertain and depends on the market and its quality as animal feed. In this study, it was assumed that the camelina meal cost the same as soybean meal, but some could argue that camelina meal has lower nutritional quality and the price should be lower. On the other hand, the demand for more locally produced feedstuffs could be a driver for higher price of camelina meal in the future. This needs to be followed closely in future assessments. As the capacity of the oil production plant influenced the oil price, feedstock availability can be an important parameter for the overall feasibility of the suggested production pathways.

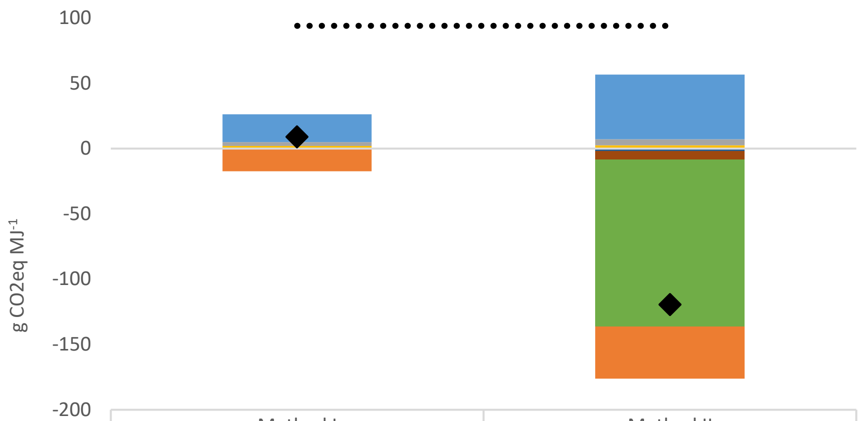
5.2 CLIMATE IMPACT

5.2.1 System I: HVO produced from *Camelina sativa* as a cover crop

The camelina-based HVO performed well in terms of climate impact, regardless of the calculation method used. The total assessed GWP for camelina HVO was 9.0 g CO_2eq MJ^{-1} with the RED II method and -119.5 g CO_2eq MJ^{-1} with the ISO method (Figure 10). Without including SOC changes, the assessed climate impact was 26.3 g CO_2eq MJ^{-1} with the RED II method and -79.4 g CO_2eq MJ^{-1} with the ISO method II.

The GWP results were dominated by the camelina cultivation step for both methods (Figure 10), with most of the emissions arising from soil N_2O emissions (61 %), and fertilizer production (31 %). The differences between the RED and ISO methods in climate impact for the cultivation step were due to their different allocation approaches. The negative CO_2 emissions due to accumulation of SOC were slightly lower than the impact from cultivation (Figure 10). However, in the ISO method, the substitution effect for camelina meal replacing soybean meal was more than threefold larger than the impact of SOC change and therefore dominated the negative emissions, resulting in a large negative total climate impact (Figure 10).

The climate impact assessed with the RED II method corresponded to an emissions saving of 90 % compared with the fossil reference (Figure 10). Even when SOC changes were excluded from the assessment, the emissions saving compared with the fossil reference was 72 %. This means that camelina HVO would meet all GHG savings thresholds currently set for current and future biofuels according to the EU Renewable Energy Directive II (European Parliament, 2018). It can also be compared to the typical value for rapeseed HVO in the Directive, which states an emissions reduction of 51 % (European Parliament, 2018). The typical values do not include any SOC changes, but the impact of the other processes can be compared. The largest absolute difference was for emissions from cultivation, where the camelina HVO had emissions of 21.5 g CO_2eq MJ^{-1} (Figure 10), and the typical value for rapeseed HVO in the Directive is 33.4 g CO_2eq MJ^{-1}. The Directive only includes further disaggregated values for soil N_2O emissions, where the typical value for rapeseed HVO is 18.0 g CO_2eq MJ^{-1} (European Parliament, 2018). The corresponding value obtained for camelina HVO was 13.2 g CO_2eq MJ^{-1}, *i.e.*, it was lower but does not explain the whole difference between the two HVO fuels. Other likely explanations for the differences are choice of fertilizer, allocation factors, and conversion ratio from seed to fuel. The largest relative difference between camelina HVO and rapeseed HVO (as described in the Directive) was for processing, with camelina HVO having emissions of 2.9 g CO_2eq MJ^{-1} (Figure 10), while the typical value for rapeseed HVO in the Directive is 10.7 g CO_2eq MJ^{-1}.



	Method I	Method II
Cropping	21,5	49,6
SOC (land use effects)	-17,4	-40,1
Oil refining and HVO production	2,9	4,6
Transport	1,9	2,5
Soybean meal substitution	0,0	-127,5
Propane substitution	0,0	-6,9
Naphta substitution	0,0	-1,8
◆ Total	9,0	-119,5
•••••• Fossil reference	94,0	94,0

Figure 10. Climate impact of camelina-based hydrotreated vegetable oil (HVO) according to the RED II method (Method I) and the ISO method (Method II), expressed in GWP_{100}, calculated including changes in soil organic carbon (SOC) as a result of camelina grown as a cover crop. "Transport" includes transportation of camelina seeds and oil.

Overall, the ISO method gave a large negative GWP value, mostly due to the substitution effect of camelina meal replacing soybean meal. The high impact of Brazilian soybean meal mainly derives from land-use change induced by expansion of soy cultivation, which in theory could be avoided by decreasing the demand for soybean meal. However, the level of GHG emissions from land use change allocated to the soybean crop varies depending on model choice and assumptions (Flysjö *et al.*, 2012). In addition, the assumption that increasing the output of one crop would decrease land use for other crops have been challenged by *e.g.*, Lambin and Meyfroidt (2011). Changing the substituted soybean meal from Brazilian to US also had a large impact on the results (Figure 11), as discussed further in the next section). Overall, the impact of soybean meal substitution was thus an important source of uncertainty for the results obtained using the ISO method. Propane and naphtha substitution also gave a negative climate impact, but much smaller than obtained for soybean meal substitution.

Scenario analysis

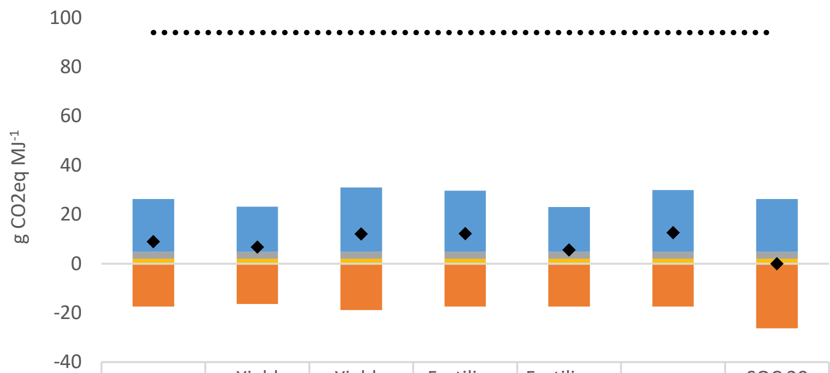
All factors tested in the scenario analysis had a similar influence on the results obtained using the RED II and ISO methods (Figures 11 and 12). However, the absolute changes were larger for the ISO method, since the RED II method allocated a fraction of the impact from cultivation to the camelina meal, while the relative changes were larger for the RED II method, since the ISO method had a strong negative impact in the base case. All cases tested in the scenario analysis, except one, gave GHG reductions of more than 65% compared with the fossil reference, even without including the impact of SOC changes. Assuming substitution of a different soybean meal ('US soybean meal') gave a climate impact of 39.9 g CO_2eq MJ^{-1} when SOC changes were excluded, which corresponded to a GHG reduction of 58% compared with the fossil reference.

Higher yield decreased the climate impact, while lower yield increased the impact (Figures 11 and 12). Higher yield increased the N_2O emissions per unit area, but also increased SOC accumulation per unit area, since more crop residues were produced. In this case, the negative climate impact of SOC accumulation was much higher than the climate impact of soil N_2O emissions. Higher yield also meant that a smaller part of the impact per unit area was allocated to each kg of camelina seed produced.

The magnitude of change from altering nitrogen fertilizer amount was similar to that of changing the yields for both methods (Figures 11 and 12). The large influence of fertilizer on cultivation emissions was because nitrogen fertilizer production and soil N_2O emissions arising from that fertilizer dominated the cultivation emissions. For the same reason, using other emission factors for soil N_2O affected the total impacts in a similar way (Figures 11 and 12).

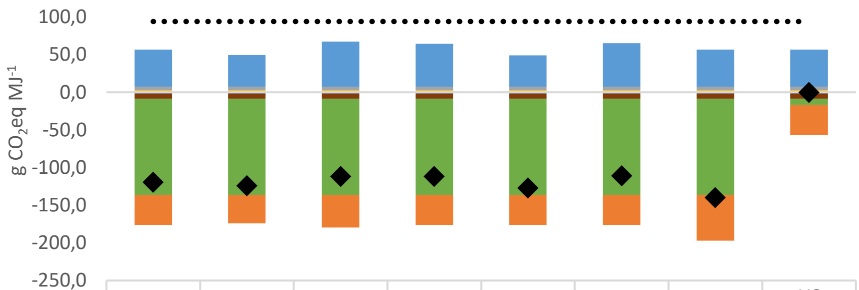
The time horizon used for calculation of SOC accumulation affected the level of negative climate impact allocated to the camelina. A shorter time horizon increased SOC accumulation per unit of camelina seed, and *vice versa*, since the SOC change is faster initially and levels out over time. A 20-year time horizon therefore decreased the climate impact per MJ camelina HVO (Figures 11 and 12).

Changing the assumed origin of soybean meal replaced by the camelina meal obtained as a by-product from oil extraction had the largest impact on calculations according to the ISO method among all variables tested in the scenario analysis. The Brazilian soybean meal assumed in the base case gave a very high negative contribution to the total impact, while using US soybean meal gave a total impact close to zero, which was closer to the results obtained with the RED II method.



	Base case	Yield +20%	Yield -20%	Fertiliser + 20%	Fertiliser -20%	N2O wet	SOC 20 years
Cropping	21,5	18,4	26,1	24,8	18,2	25,1	21,5
SOC (land use effects)	-17,4	-16,4	-18,8	-17,4	-17,4	-17,4	-26,3
Oil refining and HVO production	2,9	2,9	2,9	2,9	2,9	2,9	2,9
Transport	1,9	1,9	1,9	1,9	1,9	1,9	1,9
Fossil reference	94,0	94,0	94,0	94,0	94,0	94,0	94,0
Total	9,0	6,8	12,2	12,3	5,7	12,6	0,0

Figure 11. Results of scenario analyses for camelina-based hydrotreated vegetable oil (HVO) according to the RED II method on: increasing or decreasing yield by 20 % (‘Yield +20 %’ and ‘Yield -20 %’), increasing or decreasing N fertilizer amount by 20 % (‘Fertilizer +20 %’ and ‘Fertilizer -20 %’), using site-dependent emission factors for soil N_2O emissions (‘N_2O wet’), and including soil organic carbon (SOC) for only the first 20 years (‘SOC 20’).



	Base case	Yield +20%	Yield -20%	Fertiliser + 20%	Fertiliser -20%	N2O wet	SOC 20 years	US soybean meal
Cropping	49,6	42,4	60,3	57,2	41,9	58,0	49,6	49,6
SOC (land use effects)	-40,1	-37,9	-43,4	-40,1	-40,1	-40,1	-60,7	-40,1
Oil refining and HVO production	4,6	4,6	4,6	4,6	4,6	4,6	4,6	4,6
Transport	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5
Soybean meal substitution	-127,5	-127,5	-127,5	-127,5	-127,5	-127,5	-127,5	-8,2
Propane substitution	-6,9	-6,9	-6,9	-6,9	-6,9	-6,9	-6,9	-6,9
Naphta substitution	-1,8	-1,8	-1,8	-1,8	-1,8	-1,8	-1,8	-1,8
Fossil reference	94,0	94,0	94,0	94,0	94,0	94,0	94,0	94,0
Total	-119,5	-124,4	-112,0	-111,8	-127,1	-111,0	-140,1	-0,2

Figure 12. Results of scenario analyses for camelina-based hydrotreated vegetable oil (HVO) according to the ISO method on: increasing or decreasing yield by 20 % (‘Yield +20 %’ and ‘Yield -20 %’), increasing or decreasing N fertilizer amount by 20 % (‘Fertilizer +20 %’ and ‘Fertilizer -20 %’), using site-dependent emission factors for soil N_2O emissions (‘N_2O wet’), including soil organic carbon (SOC) for only the first 20 years (‘SOC 20’), and assuming that camelina meal replaces US soybean meal instead of Brazilian soybean meal (‘US soymeal’).

Time-dependent temperature response

The time-dependent temperature response showed a similar trend to the estimated GWP, with both methods giving a significantly lower climate impact for camelina HVO than the fossil reference throughout the whole study period (Figures 13 and 14). According to the ISO method, camelina HVO gave a net negative temperature response throughout the whole study period (Figure 14), while the RED II method gave a net negative temperature response only during the first 30 years (Figure 13). The reason why the total impact changed from net negative to net positive was that SOC accumulation leveled off over time.

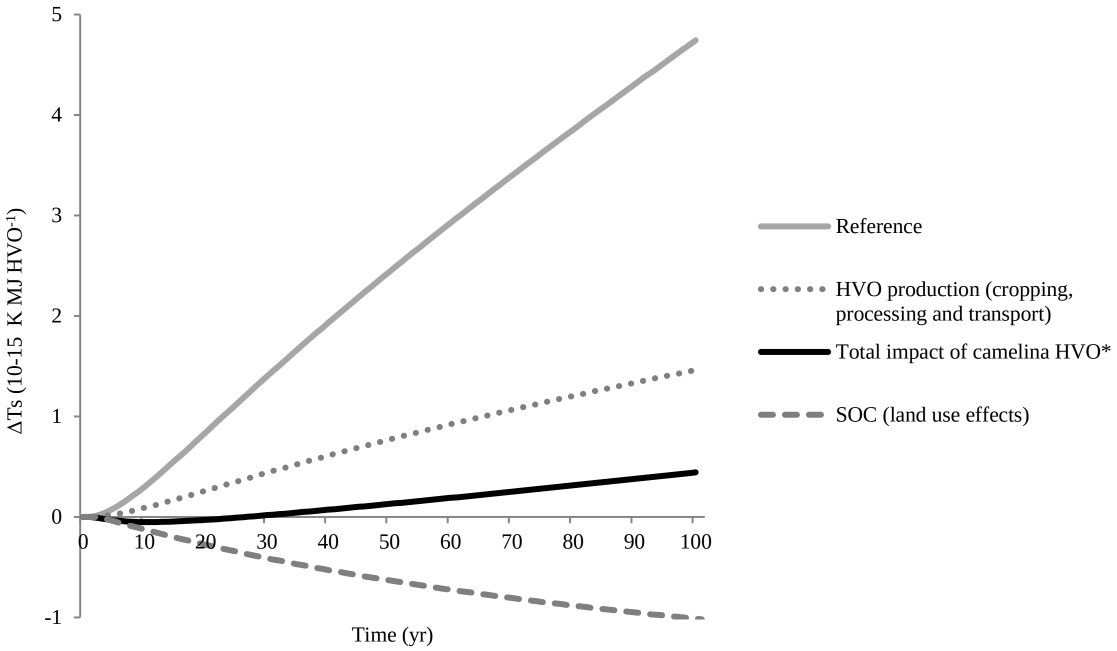


Figure 13. Temperature response of camelina-based hydrotreated vegetable oil (HVO) according to the RED II method, expressed over 100 years from introducing camelina as a cover crop. SOC=soil organic carbon.

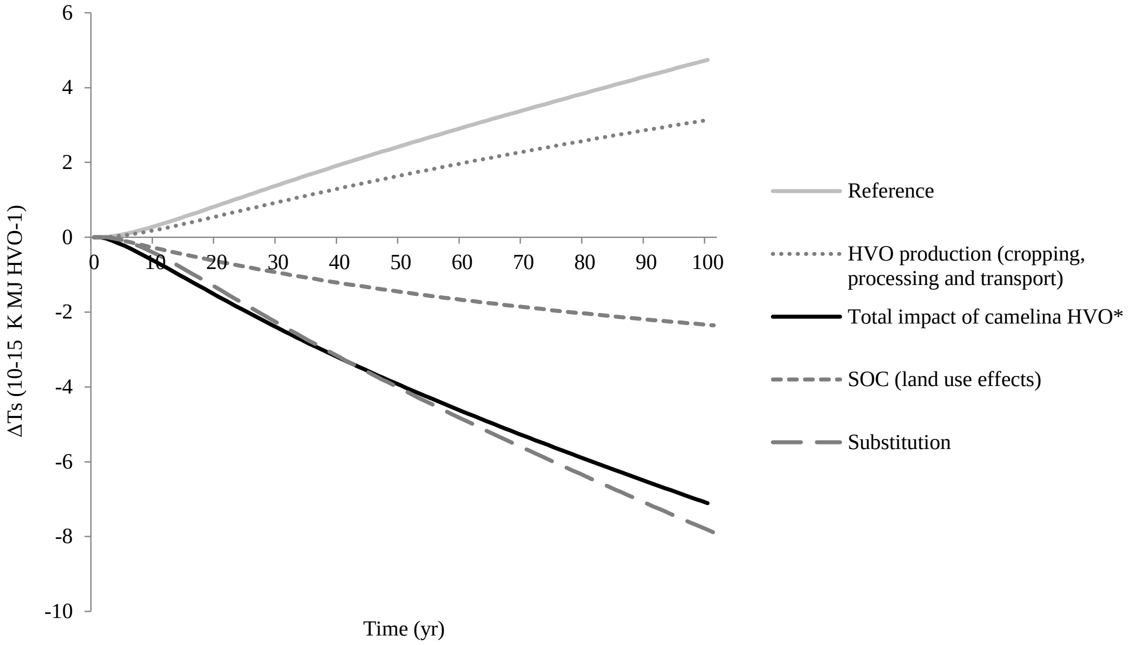


Figure 14. Temperature response of camelina-based hydrotreated vegetable oil (HVO) according to the ISO method, expressed over 100 years from introducing camelina as a cover crop. SOC=soil organic carbon.

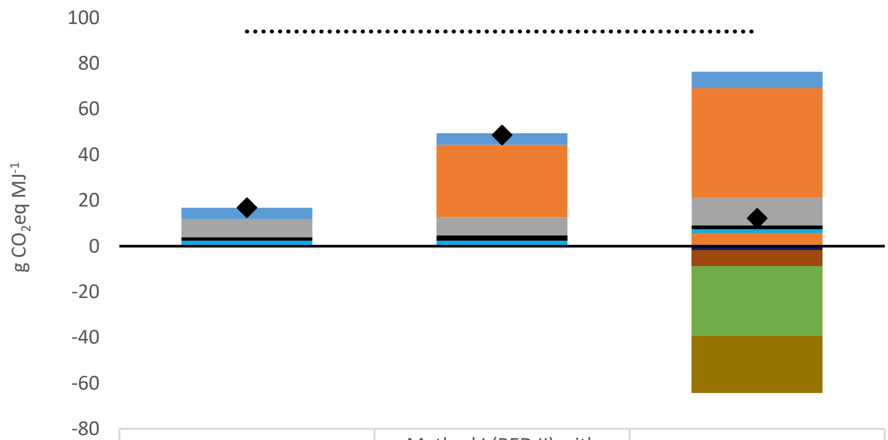
5.2.2 System II: HVO produced from forest residues (tops and branches) using oleaginous yeast

Biogenic carbon stock changes from harvesting forest residues had the largest impacts on GWP, calculated over 90 years, according to both the RED II and ISO methods (Figure 15). Apart from biogenic carbon fluxes, the impact of biochemical conversion of forest residues to MO and biomass harvesting and transport made a fairly high contribution to overall climate impact, while the contribution from transportation of oil and HVO was less important. Calculated with the RED II method and without biogenic carbon emissions, the fuel gave an 82 % reduction compared with the fossil fuel reference given in the EU Renewable Energy Directive II (European Parliament, 2018). When including biogenic carbon changes over 90 years, the GHG reduction was 48 %, meaning that when biogenic carbon changes for a forest stand in central Sweden were included the fuel did not meet the reduction target in the Directive (65 % reduction).

In the RED II method, including biogenic carbon fluxes from forest residue harvesting is not a requirement, as long as land use criteria are met (*i.e.*, no land use change or use of protected land). Comparing the GWP results obtained here using the RED II method to typical values presented in the Directive for other fuels produced from *waste wood*, the estimated GHG reduction was similar to the typical values for *e.g.*, *waste wood Fischer-Tropsch diesel in free standing plant* (85 %) and similar fuels (European Parliament, 2018). This indicates that HVO obtained from forest residues via oleaginous yeast conversion performs similarly from a GHG perspective to Fischer-Tropsch diesel produced from the same biomass. Waste wood is categorized together with forest residues in Annex IX of the Directive (European Parliament, 2018). The climate impact due to biogenic carbon changes as a result of forest residue removal is discussed below. Soam and Börjesson (2020) calculated the climate impact of HVO from forest residues via fast pyrolysis to be around 9 g CO_2eq MJ$^-$

[1] fuel, which is almost half the estimated impact in the present study. This is likely due to higher conversion efficiency assumed in the study by Soam and Börjesson (2020).

Substitution effects of the by-products when using the ISO method greatly influenced the results. Electricity and biogas generated in the biochemical conversion process step had the largest substitution effects, because of the rather large quantities of these by-products. Nitrogen fertilization to compensate for nitrogen removed with the forest residues proved to be rather important for total climate impact, of the same magnitude as biomass harvesting and transport (Figure 15).



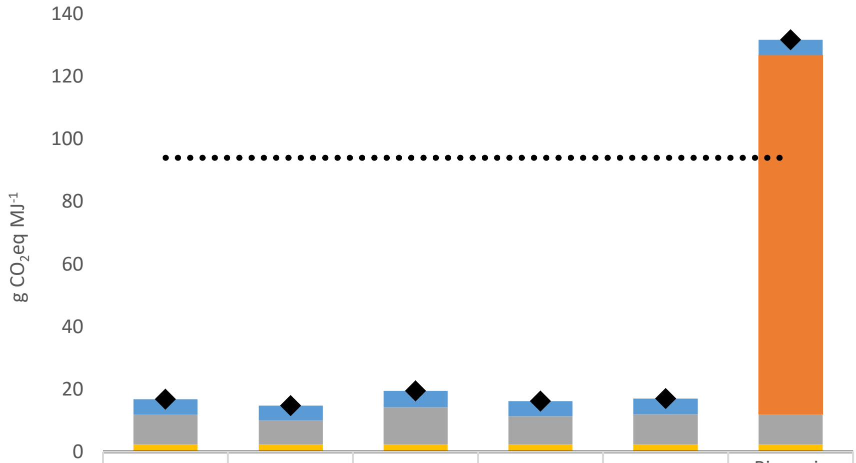
	Method I (RED II)	Method I (RED II) with biogenic carbon emissions	Method II (ISO)
Forest residue harvest and transport	4,9	4,9	7,0
Land use effects (biogenic carbon changes)		31,8	48,2
Biochemical conversion MO	8,0	8,0	12,1
HVO production	1,5	2,4	1,6
Transport to and from HVO conversion plant	2,4	2,4	1,6
Nitrogen compensation			5,9
Electricity substitution			-24,9
Biogas substitution			-30,6
Propane substitution			-6,9
Naphtha substitution			-1,8
◆ TOTALT	16,8	48,6	12,2
········· Fossil reference	94,0	94,0	94,0

Figure 15. Climate impact (GWP_{100}) of hydrotreated vegetable oil (HVO) produced from forest residues, calculated using the RED II method (Method I) and the ISO method (Method II) including changes in biogenic carbon flows as a result of increased forest residue harvesting over 90 years.

Scenario analysis

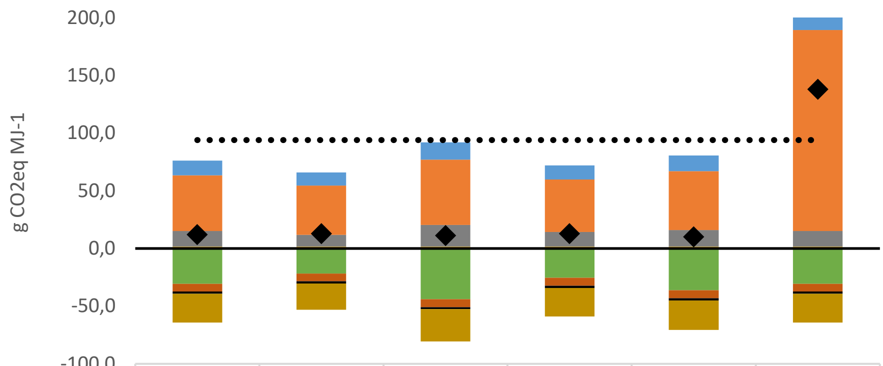
Results from the scenario analyses are presented in Figure 16 (RED II method) and Figure 17 (ISO method). Lipid yield during lipid fermentation (percentage of lipids in cells at the end of fermentation) affected HVO production, but also biogas production, since biogas was assumed to be produced from the yeast biomass. Similarly, extraction losses affected HVO production, but since the MO oil lost during extraction contributed to biogas production, the overall effect of lower HVO production (scenario with extraction losses 15 %) did not affect the results to a great extent. The effect of higher biogas production in the scenarios with lower MO production was more evident when using the ISO method, as the substitution effects were higher for biogas in those scenarios.

Regarding biogenic carbon dioxide emissions, the change between the reference forest management, *i.e.*, leaving forest residues on-site, and a system where the forest residues were harvested for biofuel production was greatest in the first years after residue harvesting. Therefore, the climate impact calculated with GWP from biogenic CO_2 was larger in a 20-year perspective than in a 90-year perspective (Figures 16 and 17). The results indicated that biofuel produced from forest residues did not have an immediate climate benefit when estimated from a stand perspective (*i.e.*, a single harvest). In fact, the climate impact during the first 20 years was 40 % higher than for the fossil reference (94 g CO_2eq MJ^{-1} fuel). The potential climate benefit seemed to emerge after more than 20 years. This is further analyzed below, using the time-dependent climate metric.



	Base case	Yield +20%	Yield -20%	Extraction 5% losses	Extraction 15% losses	Biogenic carbon 20 years
Forest residue harvest and transport	4,9	4,7	5,3	4,8	5,0	4,9
Land use effects (biogenic carbon changes)	0,0					114,9
Processing (biochemical conversion and HVO production)	9,5	7,7	11,8	9,1	9,7	9,5
Transport	2,4	2,4	2,4	2,4	2,4	2,4
◆ TOTALT	16,8	14,7	19,5	16,3	17,1	131,7
•••••• Fossil reference	94,0	94,0	94,0	94,0	94,0	94,0

Figure 16. Results of scenario analysis for hydrotreated vegetable oil (HVO) based on microbial oil (MO) produced from forest residues according to the RED II method on: increasing or decreasing the MO yield by 20 % ('Yield +20 %' and 'Yield -20 %'), altering losses during MO extraction ('Extraction 5 %' losses and 'Extraction 15 % losses'), and considering biogenic carbon over 20 years ('Biogenic carbon 20 years').



	Base case	Yield +20%	Yield -20%	Extraction 5% losses	Extraction 15% losses	Biogenic carbon 20 years
Forest residue harvest and transport	12,9	11,4	15,1	12,2	13,7	12,9
Land use effects (biogenic carbon changes)	48,2	42,6	56,5	45,6	51,0	174,1
Processing (biochemical conversion and HVO production)	13,7	10,4	18,8	12,6	14,4	13,7
Transport	1,6	1,6	1,6	1,6	1,6	1,6
Electricity substitution	-24,9	-22,8	-28,1	-24,9	-25,6	-24,9
Naphtha substitution	-1,8	-1,8	-1,8	-1,8	-1,8	-1,8
Propane substitution	-6,9	-6,9	-6,9	-6,9	-6,9	-6,9
Biogas substitution	-30,6	-21,7	-43,9	-25,5	-36,3	-30,6
TOTALT	12,2	12,8	11,4	13,0	10,1	138,1
Fossil reference	94,0	94,0	94,0	94,0	94,0	94,0

Figure 17. Results of scenario analysis for hydrotreated vegetable oil (HVO) based on microbial oil (MO) produced from forest residues according to the ISO method on increasing or decreasing the MO yield by 20 % ('Yield +20 %' and 'Yield -20 %'), altering losses during MO extraction ('Extraction 5 %' losses and 'Extraction 15 % losses'), and considering biogenic carbon over 20 years ('Biogenic carbon 20 years').

Time-dependent temperature response

Biogenic carbon emissions from forests can be accounted for using different perspectives, two of which are illustrated in Figure 18. The first approach (left in Figure 18) is a stand perspective, where a one-time harvest takes place and the biogenic carbon fluxes from combusting 1 MJ of forest residues directly are compared with a reference with no harvest of forest residues (where the biomass is left to decompose). This approach results in a high initial temperature response which decreases over time, as the difference in biogenic carbon flux between the reference and the residue harvest scenario decreases with time. The second approach (right in Figure 18) is a landscape perspective, where forest residues are harvested every year from different stands in a landscape. The temperature response of harvesting and combusting 1 MJ of forest residues for a landscape perspective, compared with a reference with no harvest of forest residues, is an initial increasing temperature curve that starts to stabilize after a few decades, when a new balanced state in biogenic carbon fluxes is reached.

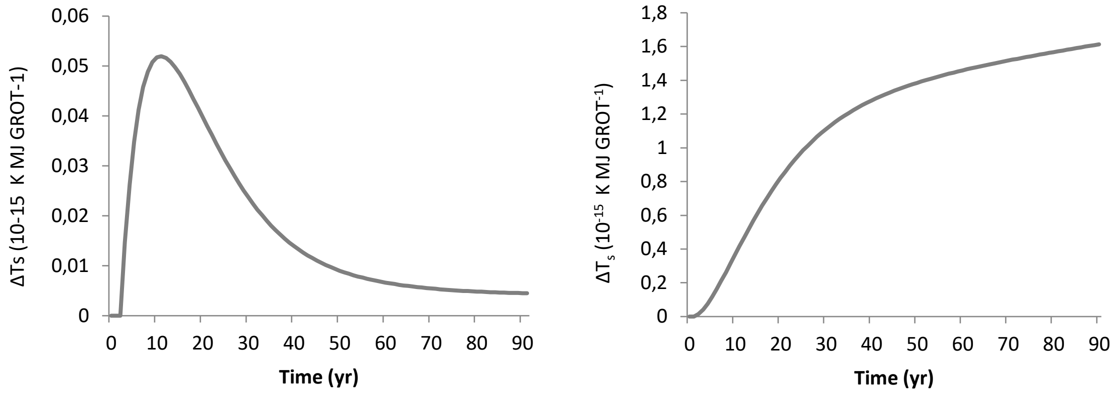


Figure 18. Temperature response in (left) a forest stand perspective (considering 1 MJ forest residues harvested in year 1) and (right) a landscape perspective, where 1 MJ forest residues are harvested every year from year 1 to year 90 (note the difference in scale on the y-axis).

As seen previously in the GWP results (base case and scenario analysis with biogenic carbon changes estimated over 20 years), the HVO produced from forest residues had a higher climate impact than fossil fuels during the first 20 years after harvest (see GWP results in Figures 16 and 17). Using the time-dependent climate metric, the temperature response of HVO produced from forest residues was lower than that of fossil fuels after 30-40 years, while the difference in temperature effects continued to increase over time (Figure 19). Using the ISO method, the substitution effects from by-products replacing fossil fuels contributed to a net negative temperature response for the total impact of MO HVO after around 55 years. It should be noted that the ΔTs values on the y-axes in Figures 19 and 20 differ from those in the graphs showing the results for camelina oil (Figures 13 and 14), because the analyses for the forest residues system were based on a stand perspective with one harvest and the following changes in relation to a reference system. For the camelina system, on the other hand, a continuous crop rotation with harvests every year was considered.

In this study, it was assumed that process emissions (transport emissions and emissions from MO and HVO production) and substituted products were unchanged during the 90-year study period. The production of inputs, fuels for transport, efficiencies in different background processes such as the production of hydrogen and enzymes, and substitution effects will likely change in the future, which is important to keep in mind when interpreting the results. As highlighted by Rummukainen (2021), the overall climate benefit from using forest products is linked to the overall societal change in response to climate change. The challenge of conducting LCA on emerging technologies and analyzing future scenarios is currently being discussed and developed within the field of LCA (Joyce & Björklund, 2021; Bergerson *et al.*, 2020). Adopting the analysis for future scenarios would not only affect the background system, but also impact the assessment of the actual forestry system, MO production process, and HVO conversion (the foreground systems), concerning process impacts, efficiencies, and future scenarios on forest management.

Clearly, the results were highly influenced by the biogenic carbon emissions (Figures 19 and 20). These were modelled for a theoretical forest stand based on current forestry management and current climate conditions, meaning that in addition to model uncertainty, the results did not take into account future management changes or changing practices in forestry. For example, Swedish forestry has undergone changes during the last 100 years that have enabled both higher production and larger carbon sink (more carbon bound in biomass) from the same quantity of forest land (IRENA, 2019). Fertilization of forests or new tree varieties could enhance growth in the future (IRENA, 2019), which would impact the carbon uptake and decrease the difference in biogenic carbon stock between harvesting and leaving forest residues on-site. Intensified forest management would affect other sustainability parameters and pose some environmental challenges with forest reside harvesting (see section 5.3.2). In the present analysis, the harvested forest residues carried the full burden from biogenic carbon emissions due to residue removal. Another approach could be to allocate the burden from losing biogenic carbon (and biogenic carbon uptake due to forest growth) between the different harvested wood products (*i.e.*, sawlogs and pulp wood) and forest residues, *i.e.*, reclassification of tops and branches from residues to primary feedstocks. However, the burden from forest management (*i.e.*, planting, thinning, and final felling) should then also be divided between the same products.

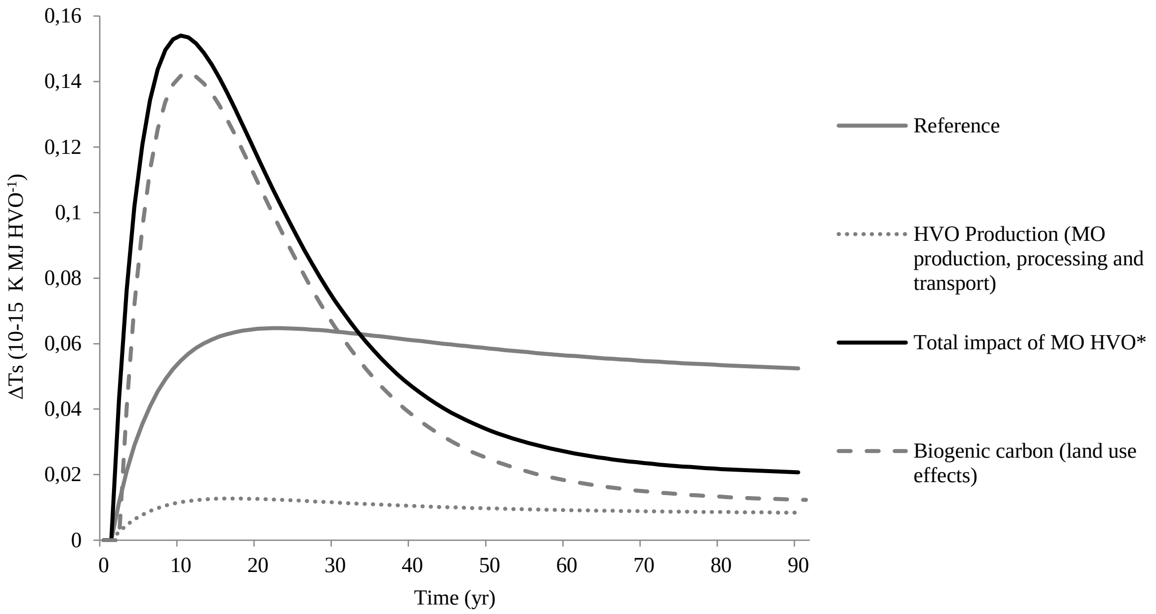


Figure 19. Temperature response of hydrotreated vegetable oil (HVO) produced from forest residues as microbial oil (MO) according to the RED II method, with biogenic carbon emissions estimated in a stand perspective over 90 years.

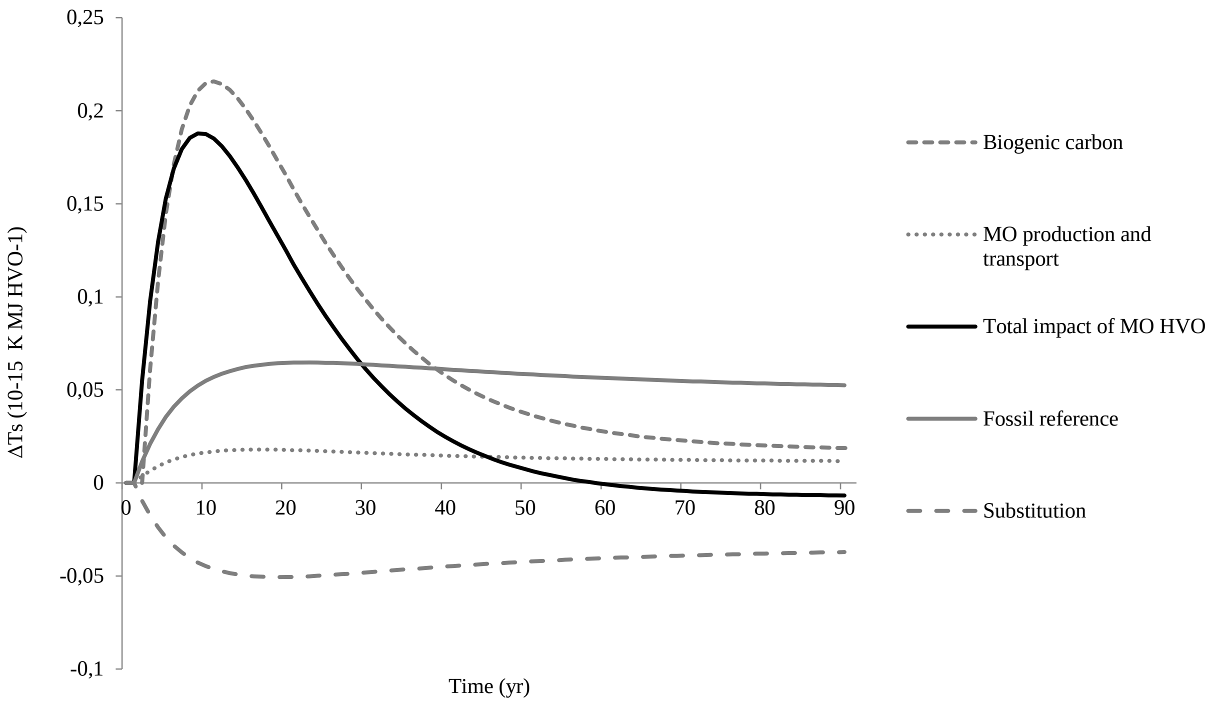


Figure 20. Temperature response of hydrotreated vegetable oil (HVO) produced from forest residues as microbial oil (MO) according to the ISO method, with biogenic carbon emissions estimated in a stand perspective over 90 years.

Biogenic carbon flows also depend on plant and soil decomposition rates, which differ depending on the climate in different regions, with shorter degradation time in southern Sweden compared with northern Sweden (Hammar *et al.*, 2015). Therefore, the assessment of when in time biofuels from forest residues have a lower temperature response than fossil fuel will depend on assumptions regarding where the forest residues are harvested. The period with higher temperature response than fossil fuels is likely to be shorter in the south and longer in the north of Sweden.

To conclude, the results obtained in this study indicated that the process emissions during production of HVO from forest residues had a relatively low climate impact compared with fossil fuels. Emissions due to changes in biogenic carbon were analyzed based on a theoretical forest stand in central Sweden (Dalarna) considering current forest growth rate and management of the forest, and the analyses showed that changes in biogenic carbon stocks can have a large influence on the overall climate impact of the fuel. Estimated time horizons in which bioenergy from forestry generates a climate benefit compared with fossil fuels varies greatly between studies (Bentsen, 2017). Multiple factors influence the long-term processes of biogenic carbon changes, which can explain the differences in results between studies. However, Bentsen (2017) found that lack of methodological consensus concerning treatment of biogenic carbon in climate impact assessments of forestry systems also contributes greatly to the differences in results. Methodological development and more thorough analysis of biogenic carbon flows in different geographical regions and forestry practices, their impacts on climate today and in the future, and impacts from a continuously changing background system (including substituted products) are needed. Increased outtake of biomass for any purpose (including non-energy purposes) affects biogenic carbon stocks. Therefore, on society level, a holistic perspective on best management and use of biomass should be developed and applied.

5.3 ENVIRONMENTAL EFFECTS (OTHER THAN CLIMATE IMPACT)

5.3.1 System I: Camelina

Introducing a new crop in the crop rotation itself increases the biodiversity, but it can also have secondary effects on other aspects of biodiversity. The potential effects include changes aboveground, in the soil, and potentially also in land use elsewhere than at the cultivation site.

Pollinating insects are an important part of the ecosystem, not least for pollinating agricultural crops (Klein *et al.*, 2007). Overwintering flowering crops like camelina can provide forage for pollinating insects early in the season, when floral resources are scarce (Eberle *et al.*, 2015). The camelina cover crop could therefore potentially contribute to improved pollination and thereby higher yields during other parts of the crop rotation. However, the effect would be dependent on factors such as presence of other flowering plants nearby during the rest of the season (Goulson, 2003).

The increase in soil organic matter resulting from the camelina cover crop can have several positive effects on biodiversity. More organic material in the soil benefits soil organism growth and diversity (Turbé *et al.*, 2010). Soil organisms are essential for organic matter turnover and for creating good soil structure (Turbé *et al.*, 2010). Increased soil organic matter content has been shown to enhance soil productivity, thereby increasing crop yields, at least under certain conditions (Henryson *et al.*, 2018; Lal, 2010). This means that camelina cultivation can enhance the output per unit of land, both by utilizing the soil during a larger part of the year and by enhancing the yields of other crops in the rotation. Intensifying agricultural production on existing farmlands may prevent conversion of other land uses into farmland elsewhere, thus avoiding losses of habitats with adverse impacts on biodiversity (Searchinger *et al.*, 2018). However, the link between intensification and avoiding land use change has been debated, and some research suggests that increased profits per unit agricultural area may increase the incentives to make more agricultural land available (Lambin & Meyfroidt, 2011). In addition, it is not clear if cultivating camelina as a cover crop would decrease the yield of the undersown succeeding crop in the relay system, in which case the output of food and feed crops would decrease and the demand for new agricultural land would increase. This effect could be partly counteracted by the decreased land use demand arising from increased SOM and substitution of soybean meal, but a thorough analysis on land use effects was beyond the scope of this report. It is thus not possible to say with certainty whether the camelina HVO would have positive or negative effects on overall biodiversity.

The eutrophication impact of camelina FAME biodiesel is reported to be dominated by emissions from fertilizer production and field emissions originating from applied fertilizers (Bacenetti *et al.*, 2017), and a similar result could be expected for camelina HVO biodiesel. The magnitude of eutrophication impact per MJ camelina biodiesel therefore to a large extent depends on how much fertilizer is required per unit of camelina seed produced. Cover crops can, under some conditions, reduce nutrient losses at field level (Aronsson *et al.*, 2016). However, that applies to cover crops that are cultivated without or with very low amounts of additional fertilizer input and instead rely on the residual nutrients from the preceding crop, which was not the case for the camelina in this study. Although camelina is often referred to as a low-input crop (Gesch *et al.*, 2014; Shonnard *et al.*, 2010; Zubr, 1997), yields in field experiments are usually also lower than for comparable oilseed crops like flax and rapeseed, giving camelina a higher eutrophication impact per unit of fuel than biodiesel from those crops (Bacenetti *et al.*, 2017). However, the camelina output per kg nitrogen fertilizer in this study was similar to that of Swedish rapeseed (Ahlgren *et al.*, 2009), indicating that nitrogen losses, and thereby the eutrophication impact from nitrogen leaching, would be similar. Fertilizer rate and camelina yield vary significantly between field experiments reported in the literature (Zanetti *et al.*, 2020; Gesch *et al.*, 2018; Berti *et al.*, 2017a; Zubr, 1997). They were therefore a large source of uncertainty in the present study, especially considering the lack of published results from field experiments with camelina in Sweden. Plant breeding could improve the yield and nutrient use efficiency of camelina (Vollmann & Eynck, 2015). It is therefore unclear if cover crop camelina HVO produced at large scale in the future would cause more or less eutrophication per MJ HVO than comparable biofuels but increasing the total input of fertilizers in the crop rotation would most likely cause higher eutrophication impact per hectare in any case.

5.3.2 System II: Forest residues

Increased outtake of forest residues to produce bioenergy has multiple effects, one of which is the impact on biogenic carbon flows and thereby on climate change, as analyzed above. However, determining the actual effect on the amount of carbon stored in biomass and soil due to different forestry management options is very complex. For example, there are secondary effects from forest residue harvesting on net carbon storage in the forest that are potentially important when analyzing the overall climate effect from increased harvesting of forest residues. First, one of the main concerns regarding forest residue harvesting is the removal of nutrients and thereby effects on future growth of the forest (Ranius *et al.*, 2018), affecting carbon stocks in the standing biomass. Tops and branches contain more nutrients than stemwood and therefore the risk of increased nutrient removal is higher when harvesting tops and branches, compared with *e.g.*, stump harvesting. Nutrient removal (primarily nitrogen) could be compensated for by adding fertilizers (see results for the ISO method above), but adding fertilizers is likely associated with other environmental concerns (Ranius *et al.*, 2018). Second, leaving tops and branches on-site may have a priming effect on the decomposition rate of older biomass in the forest (Ranius *et al.*, 2018). This could result in slower decomposition rate of the remaining biomass when forest residues are harvested.

Increased outtake of forest residues is also likely to have other environmental effects (apart from affecting the biogenic carbon flows), some of which are described/discussed below. Essentially, many of the environmental concerns associated with forest residue harvesting are negative effects on ecosystem services that intense forestry is already having, but which risk being enhanced by further intensification such as forest residue harvesting (Ranius *et al.*, 2018; Berger *et al.*, 2013).

The export of nutrients, primarily nitrogen, due to increased export of nutrient-rich biomass (tops and branches) may affect long-term growth, as described above. However, nutrient removal may also decrease leaching of nitrogen to water, which often occurs following a clear-cut. In a review, Ranius *et al.* (2018) showed that a majority of studies on growth effects of harvesting tops and branches during final felling found no effect in Norway spruce, but many studies also found a negative effect on growth and a smaller number of studies a positive effect. Ranius *et al.* (2018) concluded that harvesting tops and branches both at final felling and at thinning poses a risk of negative effects on growth.

Harvesting forest residues may lead to increased acidification of forest soils due to removal of base cations. To compensate for this effect, it has been recommended that part of the ash from biomass combustion be recycled to the forest site (Ranius *et al.*, 2018; de Jong, 2014).

Forest residue harvesting affects biodiversity in many ways. First, it results in loss of potential habitat as more biomass is removed from the forest. Second, it affects soil-dwelling organisms since more heavy machinery is operated in the forest. Third, biodiversity can be affected by increased acidification due to forest residue harvesting. Fourth, aquatic organisms may be affected through nutrient leaching and leaching of heavy metals following residue harvesting. Fifth, forest residue harvesting may affect understory vegetation, meaning that organisms which live there may be affected (Ranius *et al.*, 2018). In summary, increased harvesting of forest residues may have multiple effects on biodiversity, many of which depend on complex interactions and are related to other environmental impacts. Intensive forestry itself of course affects biodiversity, and increased outtake of forest residues can risk magnifying this impact.

A specific concern related to harvesting of forest residues is that piles of forest residues stored for a long time before being picked up can act as egg-laying sites for insects and, when the biomass is burned or further treated, the eggs are destroyed (Ranius *et al.*, 2018). For tops and branches this has only been studied for oak, which is not a major tree species within intensive northern European forestry (Ranius *et al.*, 2018).

Concerns have been raised that harvesting forest residues increases the risk of leaching of heavy metals, especially mercury (Hg) (Ranius *et al.*, 2018; de Jong, 2014), but no strong evidence of this has been reported in the literature (Ranius *et al.*, 2018).

Lastly, there might be some positive effects from forest residue harvesting, one being potentially lower pest pressure (Ranius *et al.*, 2018).

5.4 GENERAL DISCUSSION

In this study, we examined biomass produced from agricultural land (camelina) and forest land (forest residues), with the latter requiring quite extensive processing before they can be used for HVO production. Thus, we studied rather different biofuel production pathways and types of biomass, although the final product, HVO, was equivalent for the two pathways.

The difference in biomass type and production pathway had implications for interpretation of the results. The results from the climate assessment and the qualitative discussion about other environmental impacts showed that environmental concerns and the climate impact of different biofuel pathways differed depending on source of biomass and conversion technology. The results were greatly influenced by how the different systems affected carbon stocks, as one system of the two systems studied had the potential to increase carbon storage as SOC (camelina planted as a cover crop) and one was associated with decreasing carbon pools in the forest (forest residue harvesting). Considering the expected increases in demand for biofuels it is important to consider how the feedstock production affects storage of biogenic carbon over time as it central for overall climate of the biofuel production system. Microbial oils could in theory be produced from any biomass that can be hydrolyzed into sugar, such as willow grown on marginal land (Karlsson Potter *et al.*, 2020) or an annual cover crop harvested as green biomass, with both these systems having the potential to increase carbon stocks belowground without competing with current food or feed production. Forest residues were selected for analysis in the present study due to the relatively high supply of this biomass in Sweden (Karlsson Potter *et al.*, 2020). Similarly, camelina could be grown as a single crop and would not then add to soil carbon compared with *e.g.*, rapeseed or other annual crops. In short, it is not the biomass itself, but the conditions for production and assumptions regarding the reference case, that are important for the resulting climate impact assessment.

6 CONCLUSIONS

In the present study, we described and assessed two pathways to produce HVO based on Swedish alternative raw materials: HVO produced from *Camelina sativa* grown as a cover crop and HVO produced from forest residues using biochemical conversion via oleaginous yeast.

The economic assessment showed that HVO produced from camelina oil can be considered a more cost-effective solution than HVO produced from microbial oil using forest residues as the main feedstock. In both assessed cases, the feedstock price was found to be a dominant parameter. The possibility for exploitation and further use of process by-products also had a strong influence on the final cost of the oil, especially in the case of camelina oil. In relation to other studies and feedstocks available in the current fuel mix, the results obtained confirmed that both feedstock alternatives can be considered interesting candidates and complement to the domestic HVO production in Sweden. However, further analysis in close collaboration with the industry is required to increase understanding of the process and uncertainties involved, and the dominant factors influencing the final cost of HVO as a result of variations in feedstock oil types and prices.

Climate impact assessments showed that camelina HVO had a GHG reduction potential of 90 % when including benefits from increased soil carbon accumulation, and 72 % reduction potential without this effect. For HVO from forest residues, the reduction potential was assessed to be 82 % when applying the RED II methodology (without biogenic carbon changes), while if biogenic carbon emissions were included in the RED II calculations the reduction potential was 48 %. When using the ISO methodology, the substitution potential of the by-products significantly influenced the results for both systems, especially replacement of soybean meal with camelina HVO. The impact of certain assumptions on important parameters, such as yield *etc*., and methodological choices were tested. Among the parameters tested, methodological choices in substituted product (origin of soybean meal) and time period considered when assessing biogenic carbon were highly influential for the results. Analysis of the temperature response over time showed that camelina HVO had an immediate climate benefit compared with the fossil reference, primarily due to SOC accumulation compared with a reference without cover crops. HVO produced from forest residues, on the other hand, showed a higher climate impact than the fossil reference for the first 30 years when analyzed in a stand perspective, after which the climate impact became lower than in the fossil fuel reference. Qualitative discussion on environmental aspects other than climate change indicated that both production systems are likely to have (positive and negative) impacts on biodiversity. There are also considerations regarding effects on biomass growth of the main crop/forest stand and nutrient availability and related aspects, such as nutrient leaching and overall productivity.

6.1 FUTURE RESEACH

Camelina grown as a cover crop was identified as an interesting option for HVO production in Sweden. However, more research is need on the applicability of camelina in Swedish agricultural systems, including suitable crop rotations, yield, input requirements and impacts on the main crop.

Biogenic carbon changes greatly impacted the climate assessments of HVO produced from forest residues. In order to improve the assessment of climate impacts over time, time dynamic assessments need to consider future scenarios on *e.g.*, forest management and growth, as well as product substitution (background system).

REFERENCES

Ahlgren, S., Hansson, P-A., Kimming, M., Aronsson, P. & Lundkvist, H. (2009). Greenhouse gas emissions from cultivation of agricultural crops for biofuels and production of biogas from manure – Implementation of the Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. Revised according to instructions for interpretation of the Directive from the European Commission.

Alonso-Ayuso, M., Gabriel, J.L., Hontoria, C., Ibáñez, M.Á. & Quemada, M. (2020). The cover crop termination choice to designing sustainable cropping systems. European Journal of Agronomy, 114, p. 126000.

Andersson, G. & Frisk, M. (2013). Forestry transports in 2010. Uppsala, Sweden.: Skogforsk.

Andrén, O. & Kätterer, T. (1997). ICBM: the introductory carbon balance model for exploration of soil carbon balances. Ecological Applications, 7(4), pp. 1226-1236.

Andrén, O., Kätterer, T. & Karlsson, T. (2004). ICBM regional model for estimations of dynamics of agricultural soil carbon pools. Nutrient Cycling in Agroecosystems, 70(2), pp. 231-239.

Andrén, O., Kätterer, T., Karlsson, T. & Eriksson, J. (2008). Soil C balances in Swedish agricultural soils 1990–2004, with preliminary projections. Nutrient Cycling in Agroecosystems, 81(2), pp. 129-144.

Aronsson, H., Hansen, E.M., Thomsen, I.K., Liu, J., Øgaard, A.F., Känkänen, H. & Ulén, B. (2016). The ability of cover crops to reduce nitrogen and phosphorus losses from arable land in southern Scandinavia and Finland. Journal of Soil and Water Conservation, 71(1), pp. 41-55.

Asmoarp, V., Davidsson, A. & Gustavsson, O. (2018). Skogsbrukets vägtransporter 2018. En nulägesbeskrivning av flöden av oförädlad biomassa från skog till industri i Sverige.Arbetsrapport 1043-2020.). Skogforsk, Uppsala. https://www.skogforsk.se/cd_20200326145316/contentassets/60da69cdf2144637a4d659d6f7df96fd/arbetsrapport-1043-2020.pdf.

Astronomy, B.D.o. Engeneering Conversion Factors.

Bacenetti, J., Restuccia, A., Schillaci, G. & Failla, S. (2017). Biodiesel production from unconventional oilseed crops (Linum usitatissimum L. and Camelina sativa L.) in Mediterranean conditions: Environmental sustainability assessment. Renewable Energy, 112, pp. 444-456.

Barta, Z., Reczey, K. & Zacchi, G. (2010). Techno-economic evaluation of stillage treatment with anaerobic digestion in a softwood-to-ethanol process. Biotechnology for Biofuels, 3(1), p. 21.

Bentsen, N.S. (2017). Carbon debt and payback time–Lost in the forest? Renewable and Sustainable Energy Reviews, 73, pp. 1211-1217.

Berger, A.L., Palik, B., D'Amato, A.W., Fraver, S., Bradford, J.B., Nislow, K., King, D. & Brooks, R.T. (2013). Ecological impacts of energy-wood harvests: lessons from whole-tree harvesting and natural disturbance. Journal of Forestry, 111(2), pp. 139-153.

Bergerson, J., Cucurachi, S. & Seager, T.P. (2020). Bringing a life cycle perspective to emerging technology development. Wiley Online Library.

Berti, M., Gesch, R., Eynck, C., Anderson, J. & Cermak, S. (2016). Camelina uses, genetics, genomics, production, and management. Industrial Crops and Products, 94, pp. 690-710.

Berti, M., Gesch, R., Johnson, B., Ji, Y., Seames, W. & Aponte, A. (2015). Double- and relay-cropping of energy crops in the northern Great Plains, USA. Industrial Crops and Products, 75, pp. 26-34.

Berti, M., Johnson, B., Ripplinger, D., Gesch, R. & Aponte, A. (2017a). Environmental impact assessment of double- and relay-cropping with winter camelina in the northern Great Plains, USA. Agricultural Systems, 156, pp. 1-12.

Berti, M., Samarappuli, D., Johnson, B.L. & Gesch, R.W. (2017b). Integrating winter camelina into maize and soybean cropping systems. Industrial Crops and Products, 107, pp. 595-601.

Blanco-Canqui, H., Ruis, S.J., Proctor, C.A., Creech, C.F., Drewnoski, M.E. & Redfearn, D.D. (2020). Harvesting cover crops for biofuel and livestock production: Another ecosystem service? Agronomy Journal, 112(4), pp. 2373-2400.

Bonatsos, N., Marazioti, C., Moutousidi, E., Anagnostou, A., Koutinas, A. & Kookos, I.K. (2020). Techno-economic analysis and life cycle assessment of heterotrophic yeast-derived single cell oil production process. Fuel, 264, p. 116839.

Brandão, M., Levasseur, A., Kirschbaum, M.U.F., Weidema, B.P., Cowie, A.L., Jorgensen, S.V., Hauschild, M.Z., Pennington, D.W. & Chomkhamsri, K. (2013). Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. International Journal of Life Cycle Assessment, 18(1), pp. 230-240.

Braunwald, T., French, W.T., Claupein, W. & Graeff-Hönninger, S. (2016). Economic assessment of microbial biodiesel production using heterotrophic yeasts. International Journal of Green Energy, 13(3), pp. 274-282.

Brentrup, F., Hoxha, A. & Christensen, B. (2016). Carbon footprint analysis of mineral fertilizer production in Europe and other world regions. 10th International Conference on Life Cycle Assessment of Food 2016. Dublin.

Brown, A., Waldheim, L., Landälv, I., Saddler, J., Ebadian, M., McMillan, J.D., Bonomi, A. & Klein, B. (2020). Advanced Biofuels—Potential for Cost Reduction. IEA Bioenergy, 88.

Brunberg, T. (2013). Bränsleförbrukning hos skogsmaskiner 2012 (Fuel consumption in forest machines 2012).nr. 789–2013). Uppsala, Sweden.: SKOGFORSK.

Castellini, M., Ubertini, S., Barletta, D., Baffo, I., Buzzini, P. & Barbanera, M. (2021). Techno-Economic Analysis of Biodiesel Production from Microbial Oil Using Cardoon Stalks as Carbon Source. Energies, 14(5), p. 1473.

Chammoun, N., Geller, D.P. & Das, K.C. (2013). Fuel properties, performance testing and economic feasibility of Raphanus sativus (oilseed radish) biodiesel. Industrial Crops and Products, 45, pp. 155-159.

Cozma, P., Ghinea, C., Mămăligă, I., Wukovits, W., Friedl, A. & Gavrilescu, M. (2013). Environmental impact assessment of high pressure water scrubbing biogas upgrading technology. CLEAN–Soil, Air, Water, 41(9), pp. 917-927.

Davis, R., Kinchin, C., Markham, J., Tan, E., Laurens, L., Sexton, D., Knorr, D., Schoen, P. & Lukas, J. (2014). Process design and economics for the conversion of algal biomass to biofuels: algal biomass fractionation to lipid-and carbohydrate-derived fuel products: National Renewable Energy Lab. (NREL), Golden, CO (United States).

de Jong, J., Akselsson, C., Berglund, H., Egnell, G., Gerhardt, K., Lönnberg, L., Olsson, B., von Stedingk, H. (2014). Consequences of an increased extraction of forest biofuel in Sweden. A synthesis from the bioenergy feedstock research programme 2007–2011, supported by Swedish Energy Agency Summary of the synthesis report. Report: ER 2014:09. Swedish Energy Agency, Eskilstuna.

De Klein, C., Novoa, R.S.A., Ogle, S., Smith, K.A., Rochette, P., Wirth, T.C., McConkey, B.G., Mosier, A., Rypdal, K., Walsh, M. & Williams, S.A. (2006). N2O Emissions from Managed Soils, and CO2 Emissions from Lime and Urea Application. In: Gytarsky, M., Hiraishi, T., Irving, W., Krug, T. & Penman, J. (eds) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Geneva: IPCC Intergovernmental Panel on Climate Change, pp. 11.1-11.54.

Eberle, C.A., Thom, M.D., Nemec, K.T., Forcella, F., Lundgren, J.G., Gesch, R.W., Riedell, W.E., Papiernik, S.K., Wagner, A., Peterson, D.H. & Eklund, J.J. (2015). Using pennycress, camelina, and canola cash cover crops to provision pollinators. Industrial Crops and Products, 75, pp. 20-25.

EEA (2021). Use of renewable energy for transport in Europe. European Environment Agency. https://www.eea.europa.eu/data-and-maps/indicators/use-of-cleaner-and-alternative-fuels-2/assessment. Accessed: 20210929.

Eliasson, L., Granlund, P., von Hofsten, H. & Björheden, R. (2012). Studie av lastbilsmonterad kross-CBI 5800 (Study of truck-mounted CBI 5800 grinder)775-2012). Uppsala, Sweden.: Skogforsk.

Eliasson, L. & Lundström, H. (2013). Skotning av hyggestorkad grot - Skotare med Hultdins Biokassett (Forwarding of dried logging residues - Study of Hultdins Biokassett) 790–2013). Uppsala, Sweden.: Skogforsk.

Energimyndigheten (2020). Drivmedel 2019 Redovisning av rapporterade uppgifter enligt drivmedelslagen, hållbarhetslagen och reduktionsplikten. Rapport ER 2020:26.

European Parliament (2018). Directive (EU) 2018/2001 of the European Parliament and of the council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) L 328/82).

Fageria, N.K., Baligar, V.C. & Bailey, B.A. (2005). Role of Cover Crops in Improving Soil and Row Crop Productivity. Communications in Soil Science and Plant Analysis, 36(19-20), pp. 2733-2757.

Fertilizers Europe (2018a). Calcium ammonium nitrate (CAN, 27% N); neutralising nitric acid with ammonia, including primary production; production mix, at plant. UUID: d069ee25-aebc-4cb5-a3b6-2b976e859d21 (version 00.00.001). GaBi database: thinkstep.

Fertilizers Europe (2018b). Potassium chloride (KCl/MOP, 60% K2O); shaft mining and benefici-ation, including primary production; production mix, at plant. UUID: a2a8695e-968c-4341-922c-a007c8a8c56d (version: 00.00.001). GaBi database: thinkstep.

Fertilizers Europe (2018c). Triple superphosphate (TSP, 46% P2O5); rock phosphate acidulation with phosphoric acid, including primary production; production mix, at plant. UUID: 8d0007f0-9ad8-43b0-86e4-ebe6e9f9d0e6 (version 00.00.001). GaBi database: thinkstep.

Flysjö, A., Cederberg, C., Henriksson, M. & Ledgard, S. (2012). The interaction between milk and beef production and emissions from land use change – critical considerations in life cycle assessment and carbon footprint studies of milk. Journal of Cleaner Production, 28, pp. 134-142.

Furusjö, E., Lundgren, J., (2017). Utvärdering av produktionskostnader för biodrivmedel med hänsyn till reduktionsplikten. Rapport nr 2017:17, f3 Svenskt kunskapscentrum för förnybara transportbränslen. Tillgänglig på www.f3centre.se

Gale, F., Valdes, C. & Ash, M. (2019). Interdependence of China, United States, and Brazil in Soybean Trade. New York: US Department of Agriculture's Economic Research Service (ERS) Report, pp. 1-48.

Gesch, R.W., Archer, D.W. & Berti, M.T. (2014). Dual Cropping Winter Camelina with Soybean in the Northern Corn Belt. Agronomy Journal, 106(5), pp. 1735-1745.

Gesch, R.W., Matthees, H.L., Alvarez, A.L. & Gardner, R.D. (2018). Winter Camelina: Crop Growth, Seed Yield, and Quality Response to Cultivar and Seeding Rate. Crop Science, 58(5), pp. 2089-2098.

Gode, J., Martinsson, F., Hagberg, L., Öman, A., Höglund, J. & Palm, D. (2011a). Miljöfaktaboken 2011 Uppskattade emissionsfaktorer för bränslen, el, värme och transporter (Book of environmental facts 2011 Estimated emissiosn factors for fuels, electricity, heat and transports). (Report 1183. Stockholm, Sweden: Värmeforsk Service AB.

Gode, J., Martinsson, F., Hagberg, L., Öman, A., Höglund, J. & Palm, D. (2011b). Miljöfaktaboken 2011. Estimated emission factors for fuels, electricity, heat and transport in sweden. Stockholm: Värmeforsk.

Goglio, P., Smith, W.N., Grant, B.B., Desjardins, R.L., McConkey, B.G., Campbell, C.A. & Nemecek, T. (2015). Accounting for soil carbon changes in agricultural life cycle assessment (LCA): a review. Journal of Cleaner Production, 104(0), pp. 23-39.

Goulson, D. (2003). Conserving wild bees for crop pollination. Journal of Food Agriculture and Environment, 1, pp. 142-144.

Greenea, 2021 Market analysis. Retreived from https://www.greenea.com/en/market-analysis/

Hammar, T., Ortiz, C., Stendahl, J., Ahlgren, S. & Hansson, P.-A. (2015). Time-Dynamic Effects on the Global Temperature When Harvesting Logging Residues for Bioenergy. BioEnergy Research, 8(4), pp. 1912-1924.

Henryson, K., Sundberg, C., Kätterer, T. & Hansson, P.-A. (2018). Accounting for long-term soil fertility effects when assessing the climate impact of crop cultivation. Agricultural Systems, 164, pp. 185-192.

Hensirisak, P., Parasukulsatid, P., Agblevor, F., Cundiff, J. & Velander, W. (2002). Scale-up of microbubble dispersion generator for aerobic fermentation. Applied Biochemistry and Biotechnology, 101(3), pp. 211-227.

Hergoualc'h, K., Akiyama, H., Bernoux, M., Chirinda, N., Prado, A.D., Kasimir, Å., MacDonald, D., Ogle, S.M., Regina, K. & Weerden, T.v.d. (2019). N2O Emissions from Managed Soils, and CO2 Emissions from Lime and Urea Application. In: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Geneva: IPCC Intergovernmental Panel on Climate Change, pp. 11.1-11.48.

Hixson, S.M., Parrish, C.C. & Anderson, D.M. (2014). Full substitution of fish oil with camelina (Camelina sativa) oil, with partial substitution of fish meal with camelina meal, in diets for farmed Atlantic salmon (Salmo salar) and its effect on tissue lipids and sensory quality. Food Chemistry, 157, pp. 51-61.

Holmgren, K., Takman, J., Vierth, I., Heyne, S., Ekström, M., Fröberg, M., Johansson, M., Karlsson, P-A. & Petrén, O. (2021). KNOGA. Fossilfri framdrift för tunga långväga transporter på väg: Kostnadsfördelning och risker för olika aktörer.

Humbrid, D., Davis, R., Tao, L., Kinchen, C., Hsu, D., Aden, A., Schen, P., Lukas, J., Olthof, B., Worley, M., Sexton, D. & Dudgeon, D. (2011). Process Design and Economics for Biochemical Conversion of Lignocelluloic Biomass to Ethanol Dilute-Acid Pretreatment and enzymatic Hydrolysis of Corn Stover. (Technical Report NREL/TP-5100-47764.

Huss, A., Maas, H. & Hass, H. (2013). Tank-to-Wheels Report Version 4.0. (JEC WELL-TOWHEELS ANALYSIS. Luxembourg: Publications Office of the European Union.

i Nogué, V.S., Black, B.A., Kruger, J.S., Singer, C.A., Ramirez, K.J., Reed, M.L., Cleveland, N.S., Singer, E.R., Yi, X. & Yeap, R.Y. (2018). Integrated diesel production from lignocellulosic sugars via oleaginous yeast. Green chemistry, 20(18), pp. 4349-4365.

IRENA (2019). Bioenergy from boreal forests: Swedish approach to sustainable wood use, International Renewable Energy Agency, Abu Dhabi.

ISO (2006a). ISO Norm 14040, Life Cycle Assessment - Principles and Framework. Environmental Management.

ISO (2006b). ISO Norm 14044, Life Cycle Assessment - Requirements and Guidelines. Environmental Management.

Joyce, P.J. & Björklund, A. (2021). Futura: A new tool for transparent and shareable scenario analysis in prospective life cycle assessment. Journal of Industrial Ecology.

Karlsson, H., Ahlgren, S., Sandgren, M., Passoth, V., Wallberg, O. & Hansson, P.-A. (2016). A systems analysis of biodiesel production from wheat straw using oleaginous yeast: process design, mass and energy balances. Biotechnology for Biofuels, 9(1), p. 229.

Karlsson Potter, H., Poulikidou, S., Henryson, K., Hammar, T. & Hansson, J. (2020). HVO produced from Swedish raw materials. Current and future potentials. Report: FDOS 07:2020.

Klein, A.-M., Vaissiere, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C. & Tscharntke, T. (2007). Importance of pollinators in changing landscapes for world crops. Proceedings of the royal society B: biological sciences, 274(1608), pp. 303-313.

Koutinas, A.A., Chatzifragkou, A., Kopsahelis, N., Papanikolaou, S. & Kookos, I.K. (2014). Design and techno-economic evaluation of microbial oil production as a renewable resource for biodiesel and oleochemical production. Fuel, 116, pp. 566-577.

Krohn, B.J. & Fripp, M. (2012). A life cycle assessment of biodiesel derived from the “niche filling” energy crop camelina in the USA. Applied Energy, 92, pp. 92-98.

Krzyżaniak, M. & Stolarski, M.J. (2019). Life cycle assessment of camelina and crambe production for biorefinery and energy purposes. Journal of Cleaner Production, 237, p. 117755.

Kätterer, T. & Andrén, O. (2001). The ICBM family of analytically solved models of soil carbon, nitrogen and microbial biomass dynamics — descriptions and application examples. Ecological Modelling, 136(2–3), pp. 191-207.

Lal, R. (2010). Beyond Copenhagen: mitigating climate change and achieving food security through soil carbon sequestration. Food Security, 2(2), pp. 169-177.

Lambin, E.F. & Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. Proceedings of the National Academy of Sciences, 108(9), p. 3465.

Lawrence, R.D., Anderson, J.L. & Clapper, J.A. (2016). Evaluation of camelina meal as a feedstuff for growing dairy heifers. Journal of Dairy Science, 99(8), pp. 6215-6228.

Lehtikangas, P. (1999). Lagringshandbok för trädbränslen, 2:a upplaga (Storage handbbok for wood fuels, 2nd edition). Uppsala, Sweden.: Swedish University of Agricultural Sciences (SLU).

Levasseur, A., Cavalett, O., Fuglestvedt, J.S., Gasser, T., Johansson, D.J.A., Jørgensen, S.V., Raugei, M., Reisinger, A., Schivley, G., Strømman, A., Tanaka, K. & Cherubini, F. (2016). Enhancing life cycle impact assessment from climate science: Review of recent findings and recommendations for application to LCA. Ecological Indicators, 71, pp. 163-174.

Li, X. & Mupondwa, E. (2014). Life cycle assessment of camelina oil derived biodiesel and jet fuel in the Canadian Prairies. Science of the Total Environment, 481, pp. 17-26.

Lindgren, M., Pettersson, O., Hansson, P-A. & Norén, O. (2002). Engine load pattern and engine exhaust gas emissions from off-road vehicles and methods to reduce fuel-consumption and engine exhaust gas emissions [in Swedish]: JTI.

Lindholm, E.L., Berg, S. & Hansson, P.A. (2010). Energy efficiency and the environmental impact of harvesting stumps and logging residues. European Journal of Forest Research, 129(6), pp. 1223-1235.

Neste, 2021 Market data. Retreived from https://www.neste.com/investors/market-data/palm-and-rapeseed-oil-prices#bdc6fd1f

Magnusson, J. & Lindblad, M. (2013). Effektivare Askåterföring (Kombimetoden). Växjö, Sweden: Linnéuniversitetet.

Marcinkeviciene, A., Boguzas, V., Balnyte, S., Pupaliene, R. & Velicka, R. (2013). Influence of crop rotation, intermediate crops, and organic fertilizers on the soil enzymatic activity and humus content in organic farming systems. Eurasian Soil Science, 46(2), pp. 198-203.

Markets insider (2021), available at: https://markets.businessinsider.com/commodities/soybean-meal-price (accessed: 20211009).

Matteo, R., D'Avino, L., Ramirez-Cando, L.J., Pagnotta, E., Angelini, L.G., Spugnoli, P., Tavarini, S., Ugolini, L., Foschi, L. & Lazzeri, L. (2020). Camelina (Camelina sativa L. Crantz) under low-input management systems in northern Italy: Yields, chemical characterization and environmental sustainability. Italian Journal of Agronomy, 15(2), pp. 132-143.

Miller, P. & Kumar, A. (2014). Techno-economic assessment of hydrogenation-derived renewable diesel production from canola and camelina. Sustainable Energy Technologies and Assessments, 6, pp. 105-115.

Mukherjee, I. & Sovacool, B.K. (2014). Palm oil-based biofuels and sustainability in southeast Asia: A review of Indonesia, Malaysia, and Thailand. Renewable and sustainable energy reviews, 37, pp. 1-12.

Mupondwa, E., Li, X., Tabil, L., Falk, K. & Gugel, R. (2016). Technoeconomic analysis of camelina oil extraction as feedstock for biojet fuel in the Canadian Prairies. Biomass and Bioenergy, 95, pp. 221-234.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T. & Zhang, H. (2013a). Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T. & Zhang, H. (2013b). Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical

Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA.

Natelson, R.H., Wang, W.-C., Roberts, W.L. & Zering, K.D. (2015). Technoeconomic analysis of jet fuel production from hydrolysis, decarboxylation, and reforming of camelina oil. Biomass and Bioenergy, 75, pp. 23-34.

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

Nilsson, D., Nylinder, M., Fryk, H. & Nilsson, J. (2012). Mätning av grotflis (Measuring of fuel chips) (in Swedish with english summary). Uppsala, Sweden.

Ogle, S.M., Wakelin, S.J., Buendia, L., McConkey, B., Baldock, J., Akiyama, H., Kishimoto, A.W.M., Chirinda, N., Bernoux, M., Bhattacharya, S., Chuersuwan, N., Goheer, M.A.R., Hergoualc'h, K., Ishizuka, S., Lasco, R.D., Pan, X., Pathak, H., Regina, K., Sato, A., Vazquez-Amabile, G., Wang, C. & Zheng, X. (2019). Cropland. In: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Geneva: IPCC Intergovernmental Panel on Climate Change, pp. 5.1-5.102.

Olofsson, J., Barta, Z., Börjesson, P. & Wallberg, O. (2017). Integrating enzyme fermentation in lignocellulosic ethanol production: life-cycle assessment and techno-economic analysis. Biotechnology for Biofuels, 10(1), p. 51.

Panoutsou, C. (2021). Sustainable biomass availability in the EU, to 2050. Imperial Collage London Consultants.

Parsons, S., Abeln, F., McManus, M.C. & Chuck, C.J. (2019). Techno-economic analysis (TEA) of microbial oil production from waste resources as part of a biorefinery concept: assessment at multiple scales under uncertainty. Journal of Chemical Technology & Biotechnology, 94(3), pp. 701-711.

Paulrud, S., Fridell, E., Stripple, H. & Gustafsson, T. (2010). Uppdatering av klimatrelaterade emissionsfaktorer (Updated climate related emission factors). SMED Report 92 2010. Norrköping, Sweden: SMHI (Swedish Meteorological and Hydrological Institute).

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P. & Smith, P. (2016). Climate-smart soils. Nature, 532(7597), pp. 49-57.

Ranius, T., Hämäläinen, A., Egnell, G., Olsson, B., Eklöf, K., Stendahl, J., Rudolphi, J., Sténs, A. & Felton, A. (2018). The effects of logging residue extraction for energy on ecosystem services and biodiversity: A synthesis. Journal of Environmental Management, 209, pp. 409–425.

Rummukainen, M. (2021). Skogens klimatnyttor – en balansakt i prioritering (utökad utgåva). CeC Syntes Nr 06 Lunds universitet.

Searchinger, T.D., Wirsenius, S., Beringer, T. & Dumas, P. (2018). Assessing the efficiency of changes in land use for mitigating climate change. Nature, 564(7735), pp. 249-253.

Shonnard, D.R., Williams, L. & Kalnes, T.N. (2010). Camelina-derived jet fuel and diesel: Sustainable advanced biofuels. Environmental Progress & Sustainable Energy, 29(3), pp. 382-392.

Sindelar, A.J., Schmer, M.R., Gesch, R.W., Forcella, F., Eberle, C.A., Thom, M.D. & Archer, D.W. (2017). Winter oilseed production for biofuel in the US Corn Belt: opportunities and limitations. GCB Bioenergy, 9(3), pp. 508-524.

Soam, S. & Börjesson, P. (2020). Considerations on Potentials, Greenhouse Gas, and Energy Performance of Biofuels Based on Forest Residues for Heavy-Duty Road Transport in Sweden. Energies, 13(24), p. 6701.

Statistics Sweden (2011). Växtskyddsmedel i jord- och trädgårdsbruket 2010. Användning i grödor.

Statistics Sweden (2020). Skörd av spannmål, trindsäd och oljeväxter. År 1965-2020. SCB statistikdatabasen. [Electronic resource] Statistical database. In: Statistics Sweden (ed. Stockholm: Statistiska centralbyrån.

Strömberg, B. & Herstad Svärd, S. (2012). Bränslehandboken 2012 (The fuel handbook 2012). (Anläggnings- och förbränningsteknik Stockholm, Sweden.: VÄRMEFORSK (Thermal Engineering Research Institute).

Swedish Forest Agency (2008). Rekommendationer vid uttag av avverkningsrester och askåterföring (Recommendations for extraction of logging residues and ash recycling) Meddelande 2/2008). Jönköping, Sweden.: Skogsstyrelsens förlag.

Tepelus, A., Rosca, P. & Dragomir, R. (2019). Biojet from hydroconversion of camelina oil mixed with straight run gas oil. Rev. Chim, 70(9).

Thorpe, R. & Ratledge, C. (1972). Fatty acid distribution in triglycerides of yeasts grown on glucose or n-alkanes. Journal of General Microbiology, 72(1), pp. 151-163.

Turbé, A., De Toni, A., Benito, P., Lavelle, P., Lavelle, P., Camacho, N.R., Van Der Putten, W.H., Labouze, E. & Mudgal, S. (2010). Soil biodiversity: functions, threats and tools for policy makers.

Vollmann, J. & Eynck, C. (2015). Camelina as a sustainable oilseed crop: Contributions of plant breeding and genetic engineering. Biotechnology Journal, 10(4), pp. 525-535.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E. & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, 21(9), pp. 1218-1230.

Wikstrom, P., Edenius, L., Elfving, B., Eriksson, L.O., Lamas, T., Sonesson, J., Ohman, K., Wallerman, J., Waller, C. & Klinteback, F. (2011). The Heureka forestry decision support system: an overview. Mathematical and Computational Forestry and Natural Resources Sciences, 3(2), pp. 87-94.

Zanetti, F., Alberghini, B., Marjanović Jeromela, A., Grahovac, N., Rajković, D., Kiprovski, B. & Monti, A. (2021). Camelina, an ancient oilseed crop actively contributing to the rural renaissance in Europe. A review. Agronomy for Sustainable Development, 41(1), p. 2.

Zanetti, F., Gesch, R.W., Walia, M.K., Johnson, J.M.F. & Monti, A. (2020). Winter camelina root characteristics and yield performance under contrasting environmental conditions. Field Crops Research, 252, p. 107794.

Zimmermann, A., Müller, L., Wang, Y., Langhorst, T., Wunderlich, J., Marxen, A., Armstrong, K., Buchner, G., Kätelhön, A. & Bachmann, M. (2020). Techno-Economic Assessment & Life Cycle Assessment Guidelines for CO2 Utilization (Version 1.1).

Zubr, J. (1997). Oil-seed crop: Camelina sativa. Industrial Crops and Products, 6(2), pp. 113-119.

APPENDIX 1

Table 1A. Electricity demand and heat demand (expressed as gross heat demand) of the biochemical conversion process for MO production.

Process	Per t biomass	Per t MO	Unit
Pretreatment			
Electricity	24	222	kWh
Heat	512	4691	kWh
Hydrolys			
Electricity	12	111	kWh
Heat	67	615	kWh
MO accumulation and yeast propagation			
Electricity	216	1981	kWh
Heat			
Lipid extraction and purification			
Electricity	34	312	kWh
Heat	132	1213	kWh
Anaerobic digestion			
Electricity	75	416	kWh
Heat	30	274	kWh
CHP			
Electricity	16	144	kWh
Heat			

Table 1B. Amount and price of materials used to estimate the OPEX of MO production.

	Amount [t year^{-1}]	Price [SEK kg^{-1}]
Sulfuric acid[1]	5 000	0.76
Enzym[2]	3 200	6.7
Ammonia[2]	1 600	1.9
Hexane	1 000	10.6

[1]Boliden (2011), [2]Olofsson et at. (2017).

Swedish Energy Agency

www.energimyndigheten.se

THE SWEDISH KNOWLEDGE CENTRE
FOR RENEWABLE TRANSPORTATION FUELS

www.f3centre.se