Colophon

Title
Conversion efficiencies of fuel pathways for Used Cooking Oil

Commissioned by
EWAB - European Waste Advanced Biofuels Association, and
MVaK - Mittelstandsverband abfallbasierter Kraftstoffe e.V.

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Review
This report was reviewed by Mr. Chris Malins of Cerulogy and Mr. Don O'Connor of S&T Squared Consultants. Comments have been considered in the final report.

Background
EWABA and MVaK contracted studio Gear Up to provide insight on key performance indicators of various used cooking oil pathways producing energy carriers for the transport sector

Date
5 February 2021

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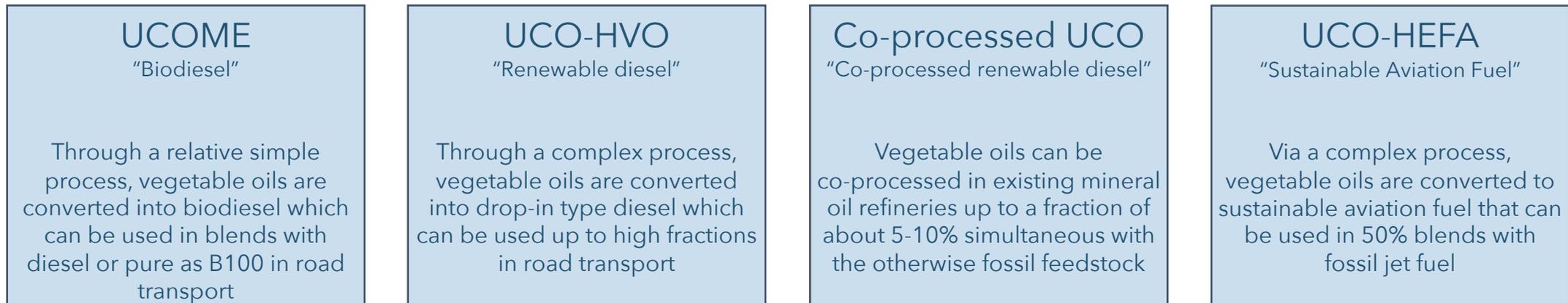# Table of contents

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Introduction

Introduction
Which UCO pathway delivers the highest environmental benefits?

Used cooking oil, known as UCO, is a waste vegetable oil from food manufacturers, restaurants, catering facilities and kitchens in schools, hospitals or households. UCO can be used to produce several types of renewable and sustainable fuel, via different pathways.

The four fuel types that are currently often considered are:

UCOME	UCO-HVO	Co-processed UCO	UCO-HEFA
"Biodiesel"	"Renewable diesel"	"Co-processed renewable diesel"	"Sustainable Aviation Fuel"
Through a relative simple process, vegetable oils are converted into biodiesel which can be used in blends with diesel or pure as B100 in road transport	Through a complex process, vegetable oils are converted into drop-in type diesel which can be used up to high fractions in road transport	Vegetable oils can be co-processed in existing mineral oil refineries up to a fraction of about 5-10% simultaneous with the otherwise fossil feedstock	Via a complex process, vegetable oils are converted to sustainable aviation fuel that can be used in 50% blends with fossil jet fuel

Each of these fuels falls in the Annex IX B category of the recast Renewable Energy Directive (RED II). The contribution of Annex IX B fuels to the RED II target of renewable energy in transport is limited to 1.7% of the energy consumption in road transport. This is actually a soft cap and Member States can implement national caps or targets higher than 1.7%.

Under the assumption that UCO is in the end limited in available volumes, EWABA and MVaK would like to understand the economic and environmental costs and benefits of using UCO as feedstock in the various pathways.

We have assessed the production costs and greenhouse gas emission performance of these production pathways, as well as several other environmental and socio-economic aspects, on basis of realistic industry data and literature.

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Main findings

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Main findings

When deployment of UCO is limited, it is best deployed as UCOME in road transport

Climate plans should focus on minimising greenhouse gas impact. In this study, we have compared four UCO pathways. We find that of all four pathways, UCOME has the lowest production costs, the highest feedstock efficiency, the highest emission reduction performance and, consequently, the lowest carbon abatement costs. This means that when the deployment of UCO is limited, it is best deployed as UCOME in road transport.

Over time, when passenger cars become largely based on electric drivetrains, UCO is still best deployed as UCOME in heavy road transport and shipping.

There is further potential to address climate impact mitigation by considering introducing higher blends (B10, B20 or B30) or even use pure UCOME (B100) in road transport.

Other UCO pathways are less favourable and only become attractive under certain conditions

An important aspect of HVO is that it allows a drop-in contribution of renewable fuels at very high blend rates. This could become an added value if the deployment of UCOME in EN590 diesel fuels would be limited due to the blend limit, of currently 7%-vol. However, in many Member States there is still sufficient room to blend FAME type biodiesel in the current fuel specifications. Moreover, fuel quality specifications can or may be changed and blend walls for UCOME can be raised accordingly. This implies that there remains potential for further UCOME blending.

Sustainable aviation fuels are an important option for climate emission reduction in the aviation sector. Governments, NGOs and the aviation sector have a focused interest to apply sustainable fuels. Within the sustainable aviation fuels portfolio, UCO based HEFA is already produced at commercial scale, due to its lower costs compared to other sustainable aviation fuels, and the preference for waste-based feedstocks.

However, from the perspective of overall climate mitigation, taking into account a wider systems approach, the use of UCO-HEFA achieves less emission reduction at higher abatement costs, compared to using UCOME in road transport.

The mitigation of the climate impact of the aviation sector may better achieved with other pathways that draw on novel and scalable feedstocks. Any use of a limited feedstock such as UCO, just moves this UCO from one sector to another while decreasing the effective contribution to decarbonisation of this feedstock.

The use of UCO in co-processing with fossil feedstocks in traditional oil refineries is limited to 5-10% of the mineral oil refinery capacity. On energy basis, co-processing is somewhat less efficient than production of HVO or HEFA in dedicated facilities, and all are less efficient than UCOME production.

# Main findings
UCOME has best greenhouse gas performance

Greenhouse gas savings

All the four pathways achieve good greenhouse gas savings when replacing fossil fuels.

UCOME achieves 10 gCO$_2$eq/MJ which implies about 90% emission reduction compared to the lifecycle emissions from fossil diesel.

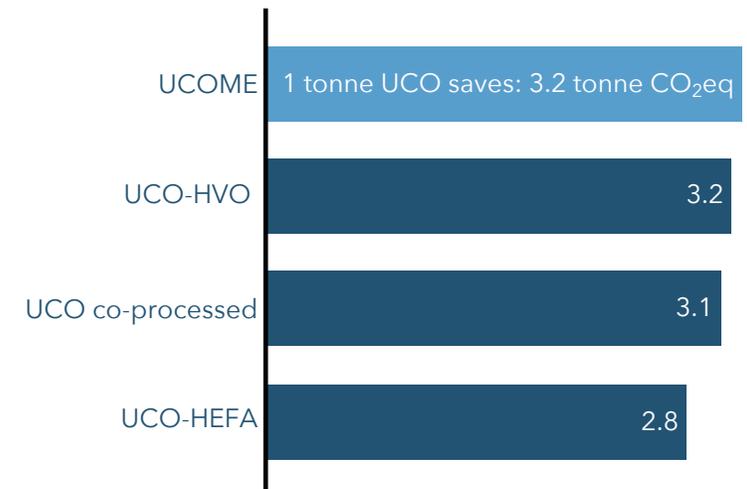HVO and co-processing have a slightly higher emission at 15 g/MJ.

The carbon footprint of HEFA is higher, at 24 g/MJ. This means that still about 75% emission reduction is achieved, which is in general good, but it is lower than for the other pathways.

Pathway	gCO$_2$eq emissions per MJ
UCOME	10
UCO-HVO	15
UCO co-processed	15
UCO-HEFA	24
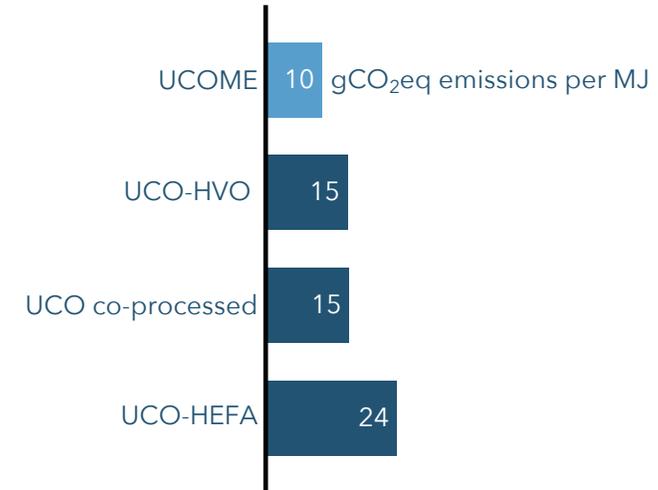
Carbon efficiency

In this case of waste feedstock, the carbon footprint hardly takes into account the conversion efficiency. This is because the emissions in the supply chain up to the point of conversion are near zero (except for some emissions from feedstock transport). Even at very low conversion efficiency, the emissions from the feedstock remain zero.

Expressed per tonne of feedstock (lower graph), UCOME achieves the highest carbon savings because it has the highest feedstock efficiency, combined with low supply chain emissions.

Pathway	1 tonne UCO saves: tonne CO$_2$eq
UCOME	3.2
UCO-HVO	3.2
UCO co-processed	3.1
UCO-HEFA	2.8

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Main findings
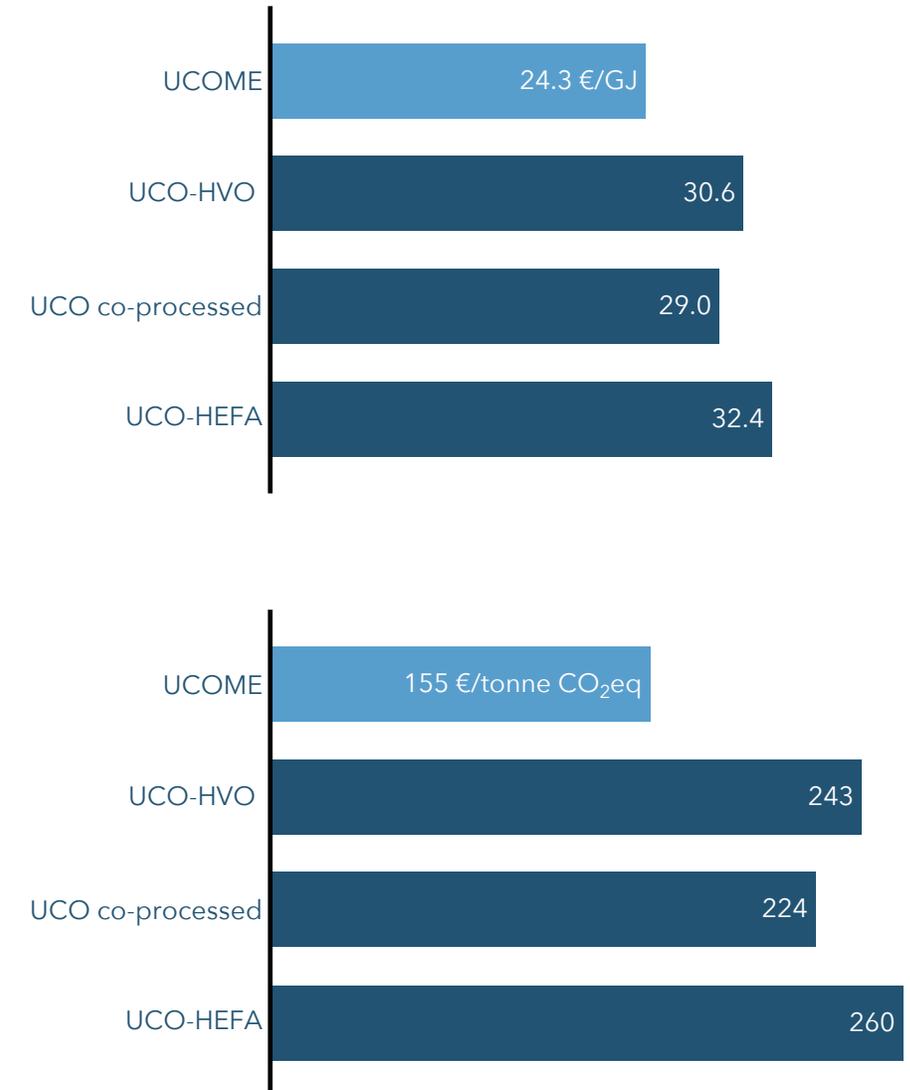# UCOME has lowest carbon abatement costs

Fuel production costs

UCOME has the lowest production costs while HEFA has highest. The feedstock costs represent the largest share of costs within each pathway, which means that the feedstock conversion efficiency becomes a determining factor. The high feedstock efficiency of UCOME production, combined with low capital costs, makes this an attractive option.

Moreover, the production scale of UCOME facilities is considerably smaller than that of HEFA or HVO production facilities.

Pathway	Cost
UCOME	24.3 €/GJ
UCO-HVO	30.6
UCO co-processed	29.0
UCO-HEFA	32.4

Carbon abatement costs

When we combine the fuel production costs with the carbon savings per unit of feedstock, we find that UCOME has the lowest carbon abatement costs of the four pathways.

Pathway	Cost
UCOME	155 €/tonne CO_2eq
UCO-HVO	243
UCO co-processed	224
UCO-HEFA	260

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Main findings
Other environmental, social and economic impacts

Environmental impacts

We have not found significant differences between pathways with respect to air quality performance. There is limited literature that offers some insight in the performance of single fuels in comparison with a fossil reference, but none that equally compares all the fuel in the current scope on an equal basis. Literature claims that some fuels perform better than others could not be substantiated.

Some past studies claimed an impact on air quality from the application of alternative fuels. In general, these studies are not useful anymore, since engines and drivetrains have improved greatly over the past decade. In general, the air quality impacts from using fuels in internal combustion engines are predominantly determined by the engine, the aftertreatment instruments (e.g. particle filters, Selective Catalytic Reduction) and the operation mode, while the fuel itself only plays a limited role. An equal comparison of fuels would require that all fuels are compared in the context of the current fleet.

Socio-economic impacts

The production of alternative fuels generates employment and income. We did not find good literature that helps to compare the employment impacts from the four pathways.

Most of the employment occurs in the phase of UCO collection – this is the same for all pathways. Since the collection takes place everywhere across the EU (and in other regions when UCO is imported to the EU), the employment is somewhat geographically distributed, with a concentration near central gathering points, such as refining and production facilities.

The typical smaller scale of production of UCOME compared to HVO, HEFA or co-processing, leads to slightly more employment per amount of fuel produced. A small plant involves relatively more people. Note that the difference cannot be large, as that would increase the production costs. Furthermore, the existing UCOME production facilities are geographically more spread than HVO, HEFA and co-processing units, which are often located in seaport locations.

Earlier UCOME production capacity investments are threatened by new UCO pathways

If the amount of UCO fuels that can be placed in the market is limited by the 1.7% soft cap (RED II), this implies that more deployment of UCO based HVO and HEFA automatically means less deployment of UCOME. The deployment of especially SAFs is stimulated via different support instruments than the deployment of road fuels. This could lead to a unequal competition for both feedstock potential *and* fuel sales.

If the deployment of UCO based HEFA and HVO is increased, this means that existing (sunken) investments in UCOME are sacrificed for investments in new fuels that are less attractive from a carbon efficiency and carbon abatement cost perspective.

Summary findings per indicator

Carbon footprint

- UCOME has the lowest GHG impact per MJ
- HEFA production has highest GHG impact per MJ
- Material efficiency does not impact footprint as UCO starts at zero
- UCOME achieves highest savings per tonne of feedstock

Air quality

- This study found no significant differences between pathways in air quality performance
- Engine and operation determine emissions more than fuel does
- Literature claims that some fuels perform better than others could not be substantiated

Production costs

- UCOME has lowest production costs while HEFA has highest
- Feedstock costs represent largest share of costs in each pathway
- Therefore, feedstock conversion efficiency is determining factor
- UCOME combines high feedstock efficiency with low capital costs

Regional added value

- Most employment occurs in UCO collection – same for all pathways
- UCOME offers slightly more employment per product output
- HVO, HEFA and co-processing often concentrated in port cities
- Difference in regional added value between fuel pathways small

Carbon abatement costs

- Carbon abatement costs of UCOME are significantly lower than of other pathways

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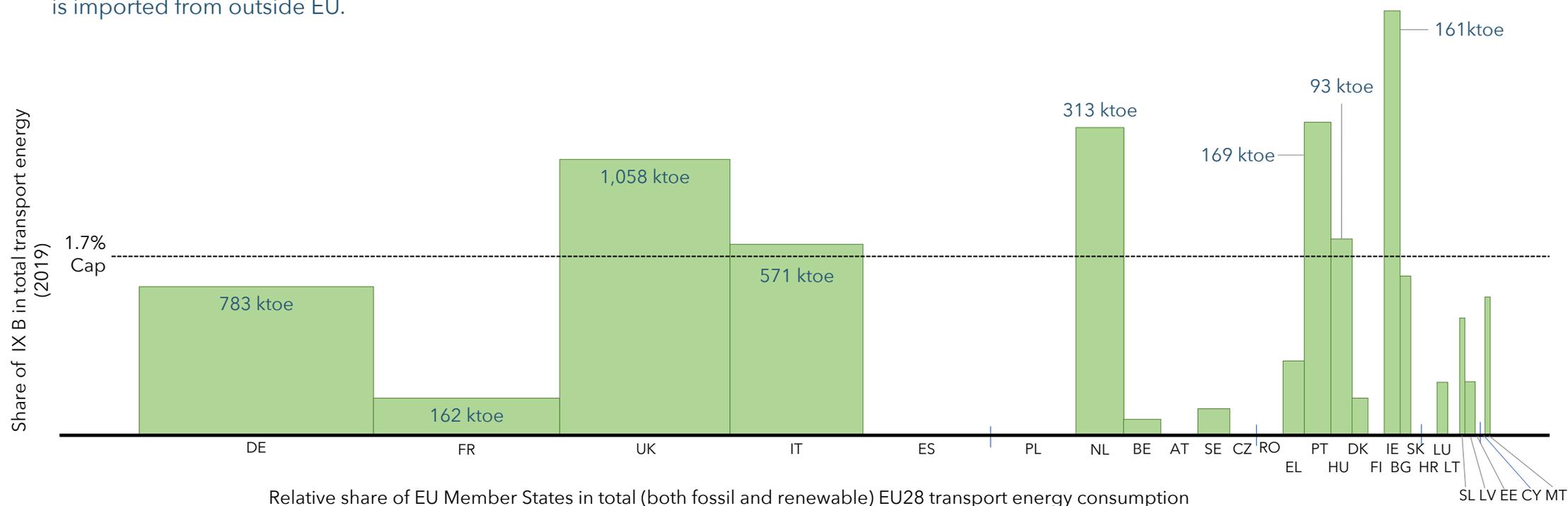
Market Context

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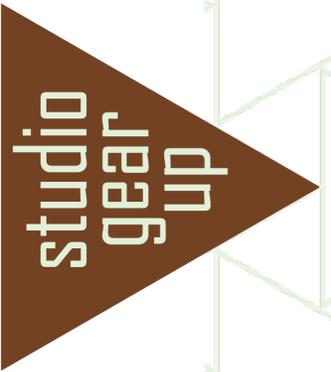
Market context
# Use of Annex IX B in EU28 Member States in 2019

Supply of, and demand for UCO based fuels

The deployment of Annex IX B biofuels, like UCOME, in the EU is currently limited by a soft cap of 1.7%. This means that Member States can only *report* up to 1.7% of these fuels in the frame of the transport target of the Renewable Energy Directive. But Member States can set higher targets for these fuels to obligated parties within their own markets. The graph below shows that the contribution of these fuels is above 1.7% in some Member States, and below in other. Overall, there is still room to increase the deployment of Annex IX B biofuels, until 1.7% is reached on an EU level.

Moreover, the collection systems for UCO in the EU are still improving and collection rates are increasing. MVaK estimated that 1.7 - 3.6 million tonne of UCO could be mobilised within the EU alone, compared to a current application of 3.5 million tonne used, of which approximately 50% is imported from outside EU.

Y-axis: Share of IX B in total transport energy (2019)

1.7% Cap

Bar labels: 783 ktoe (DE), 162 ktoe (FR), 1,058 ktoe (UK), 571 ktoe (IT), 313 ktoe (NL), 169 ktoe, 93 ktoe, 161 ktoe

X-axis labels: DE, FR, UK, IT, ES, PL, NL, BE, AT, SE, CZ, RO, EL, PT, HU, DK, FI, IE, BG, SK, HR, LT, LU, SL, LV, EE, CY, MT

Relative share of EU Member States in total (both fossil and renewable) EU28 transport energy consumption

Sources: EU potential estimated by MVaK, presented at the 2017 Fuels of the Future conference. Current application and import from Eurobserver Biofuels Barometer 2019. Chart based on Eurostat SHARES.

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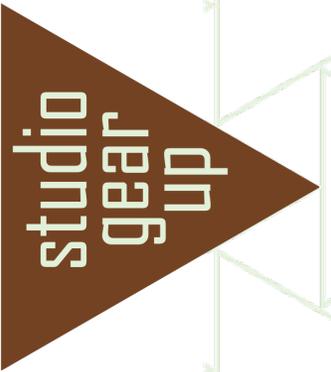
Reflection on literature

Existing literature allows limited comparison of UCO pathways

Greenhouse gas performance

Many studies evaluate the greenhouse gas performance of UCOME and UCO based HVO, but there is limited earlier work on the greenhouse gas performance of HEFA and fuel via co-processing of UCO in fossil refineries.

However, we did not find a study that compares the greenhouse gas performance of all four pathways on basis of the same underlying parameters and factors. Annex V of the Renewable Energy Directive includes typical supply chain greenhouse gas emissions for UCOME and UCO based HVO, but not for the others. Moreover, the underlying parameters are unknown, so that it cannot be judged if the performance is representative for the current market.

Economic performance

Some studies evaluate the economic performance. For instance, a 2018-study by (S&T)[2] provides much technical detail, including mass and energy balances for the production of UCOME, HVO and HEFA. We did not find any detailed economic analysis on co-processing. Outcomes from separate studies cannot easily be compared, especially because the cost of feedstock and revenues from main co-products fluctuate in time and quickly lead to lower or higher production costs. Nevertheless, such studies provided useful elements for the calculations in the present study.

Environmental impacts

Analysis of environmental impacts related to biofuels in literature mainly covers feedstock sustainability, which is not a distinctive aspect in the current study. We have not found any discussion on lifecycle impacts other than the climate impact. An understanding of impacts caused by material use and waste treatment from the production facilities would require full LCA analysis. We think this would not lead to major impact differences between the four production pathways, since these impacts are often regulated and limited by permits and legislation.

Some literature exists on air quality impacts from the use of the fuels. This relates mainly to local pollutants such as particulate matter (pm), SO_x and NO_x. SO_x emissions from all UCO based fuels are zero, because the fuel does not contain sulphur. As we will explain later in more detail, the type of engine and operation mode have more impact on pm and NO_x emissions than the fuel has. Studies on emissions from biofuels in internal combustion engines, published 5-10 years ago have limited value because engines and drivetrains have greatly improved and with the newest generation engines, the emission of NO_x and pm from all fuels are low.

Socio economic impacts

We have not found any literature that allowed for a comparison of socio-economic impacts, such as employment or contribution to rural economy between the four UCO fuel pathways.

Literature used for modelling impacts

Modelling cost and climate performance

In the current study, the greenhouse gas impact and production costs have been calculated on basis of a single dataset. Where applicable, the same factors where used for all all or some pathways, such as the cost of UCO feedstock, other materials and energy, or the impact factors of energy and materials.

Harmonisation of feedstock characterisation

Existing literature lacks alignment in feedstock. In the current study the pathways are compared on with one feedstock definition. This is important because it impacts yields, mass and energy balances:

- Feedstock quality determines the level and costs of cleaning and material loss.
- Feedstock origin impacts molecular structure which impacts mass balance, via the chain length and amount of double bonds.
- Feedstock costs determine >70% of production costs and vary strongly in time.

Useful elements from literature

Especially the study by (S&T)[2] provided much insights in mass and energy balances for UCOME, UCO-HVO and UCO-HEFA pathways. The data was complemented with other studies (see footnote). Impact factors have mainly been taken from Biograce version 4d.

Expert consultation

All mass and energy balances, and cost parameters were reviewed by Dr. Slade of REG, Dr. Düker of KFS Biodiesel and Dr. Türck of Tecosol. This led to further improvement of mass and energy balances and further notions on shortcomings in existing literature:

- Much existing literature on UCOME outdated, whereas HEFA based on projections
- (Certified) industry data would be needed for best comparison
- HVO/HEFA yields and hydrogen consumption are related via the process focus on hydrogenation or decarboxylation. One cannot have a low hydrogen consumption (in case of more decarboxylation) and a high product yield (in case of more hydrogenation) at the same time. Hence, one cannot have a low greenhouse gas impact and high product yield at the same time.
- LPG co-production increases (external) process energy consumption. This should be accounted for in calculations.

Sources: (S&T)[2], 2018, Description and data collection on biofuel technologies. Behrends, 2018, Greenhouse gas footprint of biodiesel production from used cooking oils. SGAB, 2017, Building up the future - Cost of biofuel. ICCT, 2019, The cost of supporting alternative jet fuels in the European Union. Antonissen, 2016, Greenhouse gas performance of renewable jet fuel: a comparison of conversion pathways. PBL/TNO, 2020, Decarbonisation options for the Dutch biofuels industry.

Detailed Results

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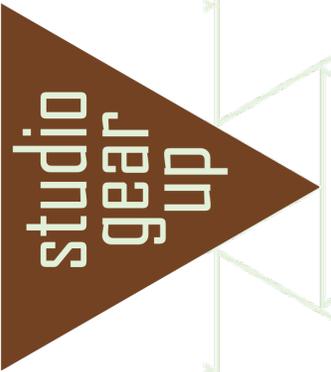
Detailed results
Carbon footprint

Main results

All pathways achieve good savings compared to fossil fuels. UCOME achieves a carbon footprint of around 10 gCO_2eq/MJ which implies about 90% greenhouse gas savings. This is in line with the typical value reported in the Renewable Energy Directive and other literature.

UCO-HVO and co-processed UCO achieve 15 g/MJ. HEFA has a higher greenhouse gas impact, of about 24 g/MJ, which still means about 75% emission reduction compared to the fossil fuel comparator.

The emission savings from UCO fuels follow from comparison with the avoided fossil emissions 95.1 g/MJ (for road and aviation fuels).[1]
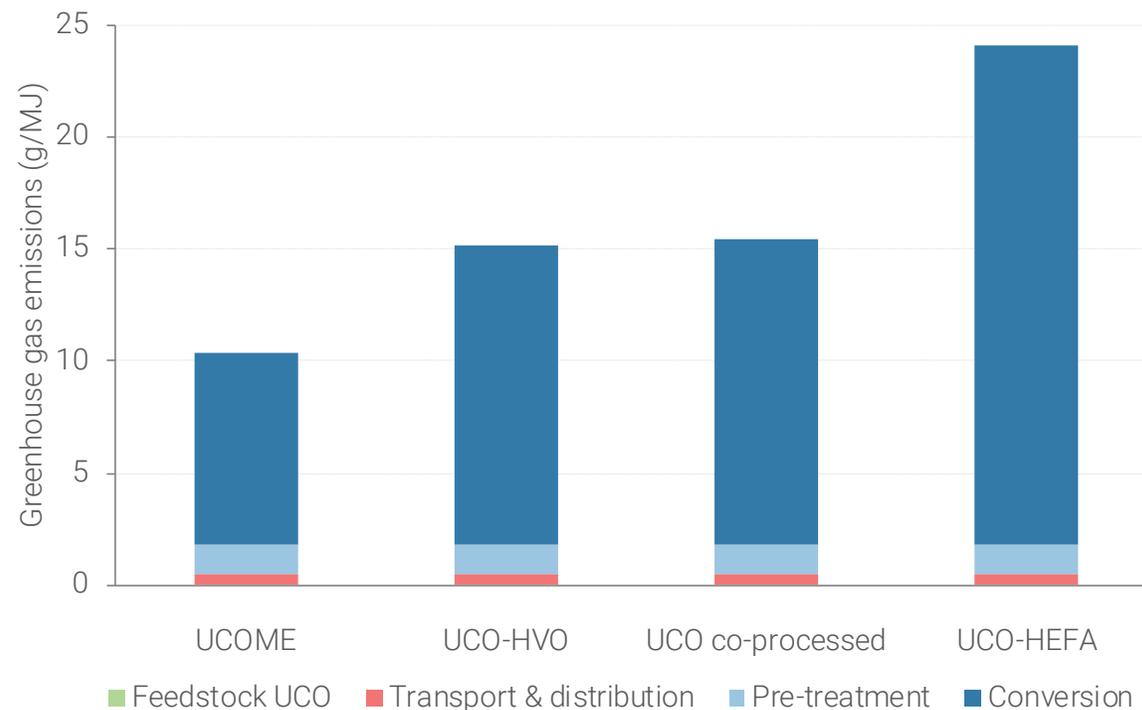
Details

The conversion step always contributes most to the carbon footprint, due to energy and methanol or hydrogen use.

The total emissions are distributed over main and co-products. Co-products carry part of the carbon emissions via energy allocation, which implies that all products within a single pathway are allocated the same emission per MJ (at the point of production). For instance, in the case of HEFA, co-produced HVO and propane have the same greenhouse gas impact.

Feedstock efficiency does not impact the greenhouse gas performance

UCO feedstock, since it is a waste product, is assumed to have zero emissions at the point of collection. This implies that a high feedstock efficiency of UCOME compared to HVO does not lead to better results. For instance, a lower conversion efficiency means more feedstock use, but if that feedstock did not lead to emissions, these will still not be visible in the end result. Obviously, sourcing feedstock over longer distances would incur transport emissions which are magnified by conversion efficiency. This would least impact the pathway with the highest conversion efficiency, i.e. UCOME.

Greenhouse gas emissions (g/MJ) for UCOME, UCO-HVO, UCO co-processed, and UCO-HEFA, broken down by Feedstock UCO, Transport & distribution, Pre-treatment, and Conversion.

[1] The reference greenhouse gas intensity for fossil diesel is 95.1 g/MJ according to Directive (EU) 2015/652. Note that some studies use 94.0 g/MJ, which is the fossil comparator from the recast Renewable Energy Directive, but this value only serves to determine compliance with the emission savings threshold, it should not be used to determine true savings.
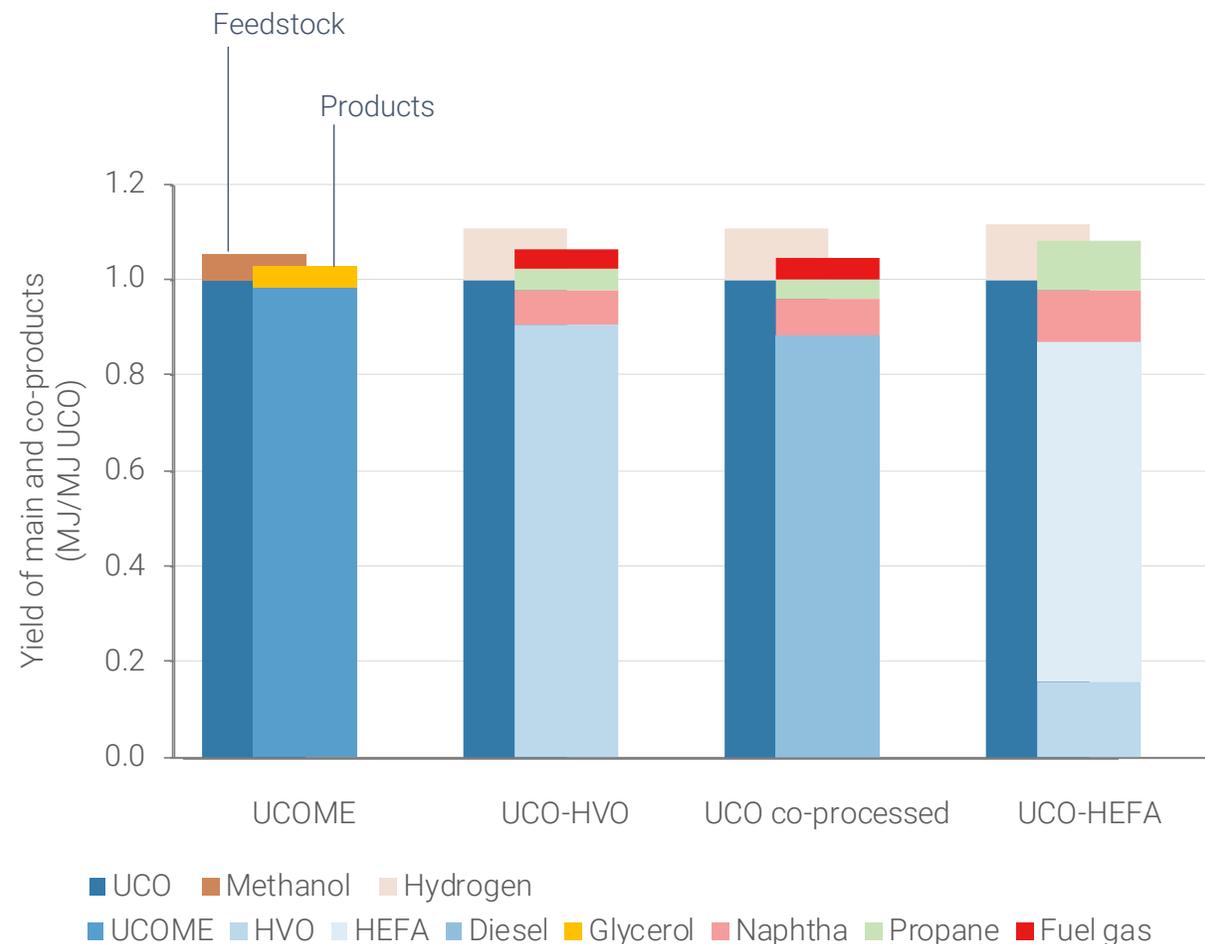
Results
Feedstock conversion efficiency

Comparison on energy basis

On a mass basis, the conversion from feedstock to UCOME is higher (104%) than to HVO, HEFA, or diesel via co-processing. In the UCOME pathway, mass is added to the fatty acid chain (part of the methanol reactant), while in the other pathways, mass is lost by removing oxygen. On an energy basis, the conversion efficiencies, from all feedstock (UCO + methanol or hydrogen) to all products and co-products are more comparable, as is shown in the figure.

The conversion efficiency to main products is highest in the UCOME pathway, while the other pathways have more co-products such as naphtha, propane and fuel gas. In the modelling, we have optimised the outputs of these co-products. In practice, depending on the set-up of a facility, part or all of the fuel gas and propane may be used to fuel the process.

Co-products cost energy

The graph does not show the external energy input (steam and electricity), which is considerably higher in the hydrotreatment pathways, especially with the production of HEFA.

Results
# UCOME has the best carbon efficiency

Main results

The overall savings per tonne of feedstock are derived by combining the savings that are achieved per unit of fuel, with the total product yield per tonne of feedstock (all products considered). We call this the carbon efficiency, to indicate how efficient a feedstock is in saving carbon emissions.

The high conversion efficiency of UCO to UCOME, combined with the low carbon footprint per MJ implies that UCOME achieves most savings per tonne of UCO feedstock.

Lower yields in the other pathways lead to lower carbon efficiencies. HEFA has the lowest carbon efficiency, mainly because of the higher greenhouse gas impact of the products (due to the high energy and hydrogen use).

In the figure, HVO, HEFA and co-processing pathways represent a maximisation of co-products. When these co-products would be used within the process, then the material yield decreases, while at the same time the greenhouse gas impact per unit of fuel improves. The result is more or less balancing, arriving at a similar net result.
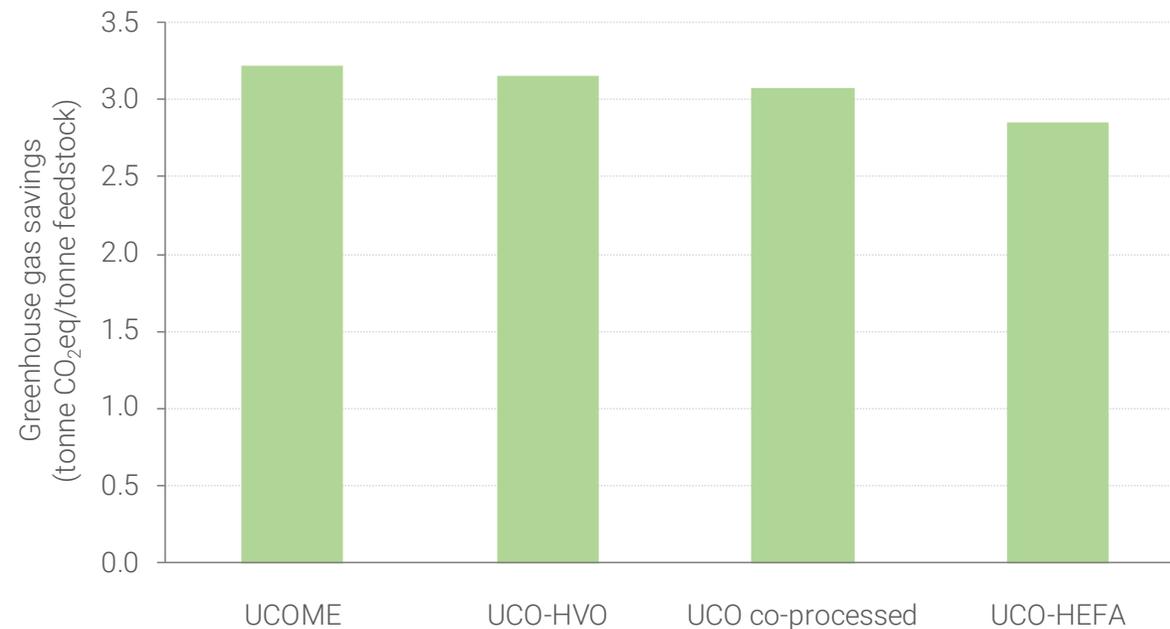
Results
Production costs

Main results

UCOME has the lowest production costs and UCO-HEFA the highest. The low costs of UCOME result from a combination (1) high feedstock efficiency towards final product and (2) simple tech with low investment costs.

The costs of UCO-HVO are somewhat higher than via co-processing. Still, co-processing is less attractive since it requires 90% fossil operation.

Feedstock costs are the most dominant factor in all four pathways. Therefore, the conversion efficiency has major impact on differentiation between the pathways.

Comparison with literature

Literature reports broad range of production costs.[1] The ranges are mainly the result of variations in feedstock costs, which fluctuate considerably over time. High feedstock costs have more impact on the pathways with lower conversion efficiency. In a relative sense, UCOME becomes even more attractive than the other options at higher feedstock costs.

The result for UCOME in our calculations is at low end of literature findings. We think this is because higher UCO prices have been assumed in the consulted literature. UCO feedstock prices fluctuated between 630 and 1200 €/tonne in recent years. In our calculations we have assumed 840 €/tonne.
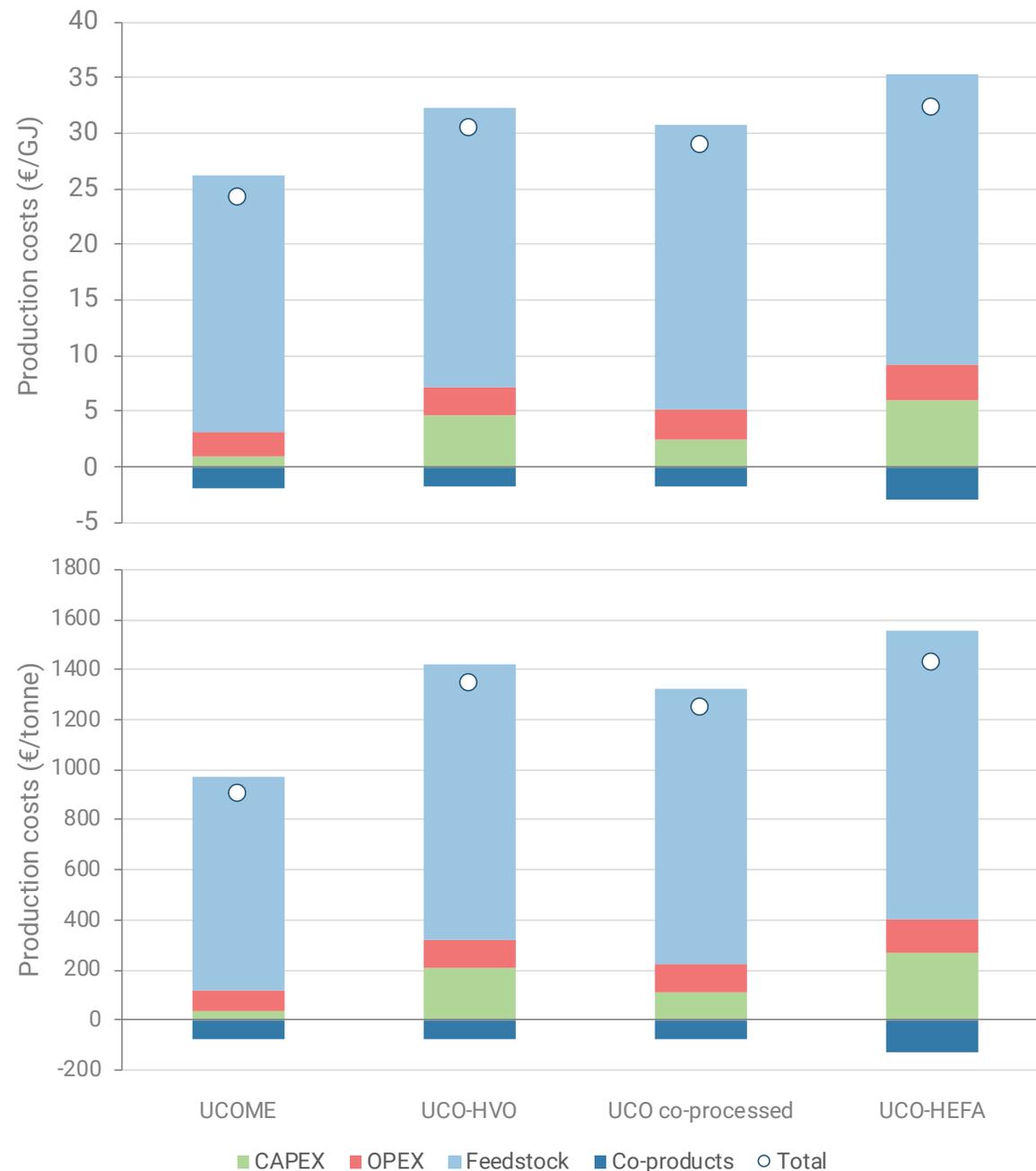
[1] In literature, UCOME costs range from 17-29 €/GJ [EC, 2016, Improving Sustainability of FAME; SGAB, 2017, Building up the future - cost of biofuels], HVO 9-14 €/GJ [SGAB], co-processed 16-33 €/GJ [SGAB], HEFA 26-30 €/GJ [De Jong et al., 2017, Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production; ICCT, 2019, The cost of supporting alternative jet fuels in the European Union].

Results
# Carbon abatement costs

Main results

The carbon abatement costs are derived by dividing the additional costs of a fuel (compared to the fossil fuel it replaces) by the savings the fuel achieves (again compared to the fossil fuel it replaces).

Since UCOME has the best results in both the carbon footprint and the production costs, the carbon abatement costs of this pathway is also significantly lower then the other pathways, with 150 €/tonne CO_2eq avoided.

The highest carbon abatement costs are associated with the HEFA pathway, with 260 €/tonne CO_2eq avoided.

Note that these outcomes are sensitive to the reference fuel prices. For instance, when fossil diesel would be 0.20 €/l cheaper, this raises the carbon abatement costs with about 70 €/tonne in all cases. On the other hand, if raw UCO becomes cheaper, then the abatement costs drop fast.

This means that the results in the graph should not be taken as absolute values. These results are not (directly) comparable with results in other studies. The relative results for the four pathways remain similar with changing diesel and UCO prices, since all four pathways depend on these prices in a similar manner.

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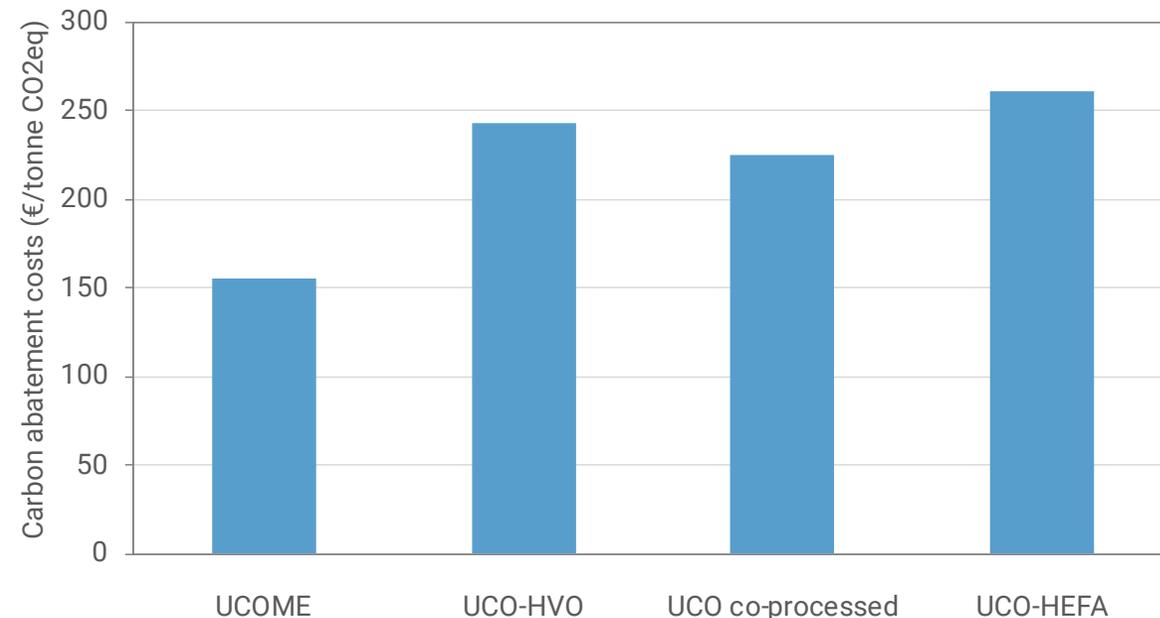
Results
Air quality

Main findings

Application of UCO produced via the four pathways probably does not lead to significant differences in vehicle exhaust emissions. Emissions of local pollutants (NO_x and fine particles) from vehicles mainly result from the type of engine, drivetrain and operation. For fuels meeting EU specifications the blending of biodiesel or renewable diesel has limited impact on the exhaust emissions.

There was some difference found in air quality impacts between the four fuel types in older engines. However, in modern engines this difference becomes negligible, both in passenger cars and heavy duty vehicles.

Euro engine standards have decreased air pollution emissions considerably over the past 30 years, both for passenger vehicles and heavy duty vehicles. For instance, Euro VI engines (heavy duty) have 60x less PM emissions and 20x less NOx emissions than Euro I engines.

Literature does not allow for full & just comparison

We found limited literature about HEFA, [1] and none about diesel via co-processing. Most literature focuses on air quality from renewable fuels compared to fossil fuels, and there is barely literature that allows for a like-for-like comparison between renewable fuels. Moreover, most of the literature relates to older engines, and is not considered representative, for the impacts today.

It is difficult, if not impossible to compare advantages of UCO fuels in road transport to advantages of UCO fuels in aviation. Savings from using HEFA happen mainly at high altitude, while savings from UCO road fuels happen close to where health impacts take place.

Air pollutant emissions by fuel from modern and older cars

Fuel	Modern cars			Older cars		
	NO_x	PM	VOCs	NOx	PM	VOCs
Diesel	🟧	🟩	🟩	🟥	🟥	🟧
FAME biodiesel	🟧	🟩	🟩	🟥	🟧	🟨
HVO	🟧	🟩	🟩	🟧	🟧	🟨

Air pollutant emissions by fuel from modern and older heavy-duty vehicles

Fuel	Modern heavy-duty			Older heavy-duty		
	NO_x	PM	VOCs	NO_x	PM	VOCs
Diesel	🟨	🟩	🟩	🟥	🟥	🟧
FAME biodiesel	🟨	🟩	🟩	🟥	🟧	🟧
HVO	🟨	🟩	🟩	🟧	🟧	🟨

Older = Vehicles that meet Euro 3 / III or equivalent (e.g. model year 2000 in Europe)
Modern = Vehicles that meet Euro 6 / VI emissions standards or equivalent.

[1] Regular fossil aviation jet fuel used to be high in sulphur to assist lubricity. Increasingly, ultra low sulphur jet fuel is used, with lubricity modifiers. HEFA does not contain sulphur, so SO_x emission reduction is 100%. In relative sense this is the same with road fuels, but in absolute sense the SO_x savings are much smaller in road transport. Fine particle emissions from aviation are mainly caused by fuel aromatics, and will significantly decrease when using HEFA. US Federal Aviation Administration reports 90% less PM emissions and 100% less sulphur emissions from using (any type of) Sustainable Aviation Fuel in comparison with fossil jet fuel [FAA 2018, Fuel Composition & Aircraft Emissions].

Sources: IEA-AMF, 2017, Air Quality Implications of Transport Biofuel Consumption; Emission standards: https://dieselnet.com/standards/eu/hd.php

Results
Regional added value

Main results

We could not find a significant difference in regional added value between the four UCO fuel pathways. We only considered employment.

Most of the employment is related to the collection of the UCO. Employment related to feedstock supply typically represents 70% of the total man days in UCO based fuel supply chains. With all pathways using the same UCO feedstock we expect no major difference in employment effects between them.

Relatively, smaller facilities have higher employment per output than larger facilities and the decentralized location often offer more social benefits to communities then large centralized locations. Since UCOME facilities typically have a smaller scale, this could create somewhat more employment, but the effect will be limited, since the production is not labour intensive.

UCOME installations are typically more geographically spread (since they originated more from local initiative rather than multinational initiative) than HVO or HEFA facilities which are often located in central port locations. Moving from rural towards central locations may impact rural employment, but the effect will be small.

Source: TNO, 2020, Total system costs RES fuels

Appendix

Parameters applied in this study

Feedstock and product definition

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Parameter assumptions
Feedstock and product definition

Same feedstock specification for all pathways

- The raw UCO has the same specification in each of the pathways assessed.

- This is necessary to allow a like-for-like comparison between the pathways.

- The main characteristics of UCO in our modelling have been set to 10% free fatty acids (FFA), 1% moisture and 1% pollutants.

Molecular structure

- All modelling is based on a narrowly defined UCO triglyceride, i.e. with a defined chain length and number of double bonds. In reality, UCO triglycerides consist of various chain lengths and double bonds, with the mix of chains depending on the feedstock. The narrow definition in the modelling facilitates comparison of yields and of hydrogen and methanol consumption between the pathways.

- In the modelling, UCO triglycerides are assumed to have an average molecular mass of 866.2 g/mole, or corresponding FFA of 276.1 g/mole. This is based on a mix of 1/3 rapeseed oil, 1/3 soybean oil and 1/3 palm oil as specified below. On average the FFA contains 17.6 C atoms and 1.2 double bonds.

- From this, the composition of free fatty acids and products, and of the hydrogen consumption, are derived in a consistent manner for all calculations.

Source assumptions

- Rapeseed triglycerides weigh 878.9 g/mole, FFA weigh 280.3 g/mole, average chain is 17.9 C & 32.3 H atoms, or 1.3 double bonds.

- Soybean triglycerides weigh 872.4 g/mole, FFA weigh 278.1 g/mole, average chain is 17.8 C & 32.6 H atoms, or 1.5 double bonds.

- Palm oil triglycerides weigh 847.5 g/mole, FFA weigh 269.8 g/mole, average chain is 17.1 C & 32.9 H atoms, or 0.7 double bonds.

Consequences

- If the UCO would be based on more palm oil, there will be less double bonds, and consequently less hydrogen required for saturation per molecule. The impact on the overall hydrogen consumption is limited because most hydrogen is required for cracking and hydrodeoxygenation (see Page 36). Palm oil has a shorter fatty acid chain, which yields somewhat less main product and more co-product in all pathways.

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Refining and degumming

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Parameter assumptions
Refining and degumming

Same refining assumed for all pathways

- Pre-treatment of UCO before fuels production consists of refining and degumming.

- We assume the same level and thoroughness of pre-treatment before all four conversion pathways.

- Actually, the pre-treatment of used cooking oil before HVO/HEFA and co-processing should be more thorough.

- The total of metal content (Fe + K + Na + Mg + Ca) before HVO/HEFA or co-processing should be below 25 ppm [UCO Trading Spain, 2019, European UCO market for 2019 – What to expect and how to understand quality and logistic issues to succeed on your export] or even 10 ppm, while it should also be low in phosphorous (<3 ppm) and chlorine (<10 ppm) and completely free of water [CMB Italy, 2020, UCO treatment].

- Content of metals, chlorine, nitrogen and unsaponifiables have a low impact on FAME biodiesel and the acceptance of phosphorous and water is slightly higher than with HVO/HEFA and co-processing [CMB Italy 2020].

- But it is unclear how this deeper feedstock pre-treatment would impact the feedstock loss, energy and material use.

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Parameter assumptions
Refining and degumming

Mass and energy balance assumptions

- We assume 1% loss through moisture, and 1% loss through pollutants [expert consultation]

- A small amount of H_3PO_4 is used for degumming. Some studies mention higher amounts of H_3PO_4 in pre-treatment for esterification of the free fatty acids. We include this esterification in the UCOME conversion step later. H_3PO_4 consumption was given as 7.95 kg per tonne of FAME [Behrends 2018], from which the consumption per tonne of feedstock was derived.

- A small amount of activated bleaching clay is used to remove metals and phosphorus components at a molecular level, and amounts typically less than 1% of the inputs [Expert consulted]. Amount ranges from 0.0003 to 0.003 kg/kg renewable fuel according to Neste [cited by PBL, 2020, Decarbonisation options for the Dutch biofuels industry]

- Energy inputs, in the form of steam and electricity are based on Neste [cited by PBL 2020]: 50 MJ electricity and 657 MJ steam per tonne of HVO. This was recalculated to inputs per tonne of raw UCO, applying the conversion efficiencies discussed below and in the HVO parameter table.

Item	Unit	Input	Output
Collected UCO	kg	1,000	
H_3PO_4	kg	7.8	
Bleaching clay	kg	1.0	
Electricity	kWh	9.8	
Steam	MJ	464	
Pre-treated UCO	kg		980
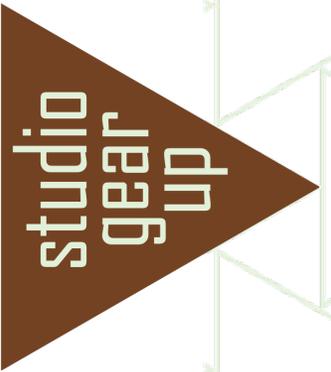
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Conversion of
pre-treated UCO to UCOME

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Parameter assumptions
Conversion of pre-treated UCO to UCOME

Mass balance assumptions

- After refining of the feedstock, the yield of UCOME is near theoretical, i.e. almost as is predicted by the chemical reaction formula.

- The theoretical yield of FAME from triglycerides is slightly above 100% by weight (for example 100.5% on basis of a vegetable oil of 866.2 g/mole, see Page 27). With increasing free fatty acids (FFA), the yield of biodiesel increases, and for 100% FFA the theoretical yield is actually 105.1% by weight (assuming FFA of 276.1 g/mole). This means that at 10% FFA the theoretical yield of FAME from feedstock will be 100.9%. In our calculation, we apply an near theoretical yield of 100.4%

- The consumption of methanol is stoechiometric or 11.0% of the biodiesel produced. However, part of the methanol is delivered by the potassium methylate catalyst, where each mole of KCH_3O replaces a mole of methanol, so that we need somewhat less methanol in practice. Note that some literature sources [Behrends] report an excess of methanol, with values up to 126.8 kg per tonne of product, but the excess is recycled, not lost.

- The very high yields of biodiesel are achieved by a potassium methylate catalyst, which at the same time the K+ catalyses the reaction and CH_3O is used in the reaction. Consumption of KCH_3O catalyst is about 10-15 kg per tonne of biodiesel [Experts consulted]. We have assumed 12.5 kg.

- In the process, first the free fatty acids are esterified by H_2SO_4, before the rest of the material is trans-esterified. The catalyst is not consumed in the reaction, but a small part is lost in the process, about 20 kg per tonne of biodiesel, or roughly 2 weight% of the feedstock [Expert consulted].

- After the acid esterification, the material is neutralised to enable the transesterification of the glycerides. This is done by adding potassium hydroxide KOH which is at the same time the catalyst for that transesterification. Since the potassium methoxide also neutralises part of the acid, somewhat less potassium hydroxide is required. The H_2SO_4 produced two H^+ ions, therefore the neutralisation requires two OH^- or CH_3O^- ions. Or, moles of KOH = 2 * H_2SO_4 – KCH_3O.

- Glycerol is co-produced, but only from the mono, di and tri-glycerides, not from the free fatty acids. However, all free fatty acid has originated from a triglyceride originally. Therefore, the amount of glycerol is taken as 1/3 of the moles of biodiesel. Note that in the mass balance glycerol molecules are presented. The sales product is crude glycerine, which typically represents 80% purity and has less value than distilled glycerine. The sales price takes this difference into account. Currently, glycerine is an important ingredient for hand-sanitizer.

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Parameter assumptions
Conversion of pre-treated UCO to UCOME

Energy balance assumptions

- The electricity consumption is 50 kWh per tonne UCOME [Expert consulted]. Literature reports a higher value of 0.08 kWh/litre UCOME which equals about 91 kWh/tonne UCOME [(S&T)2, 2018, Description and data collection on biofuel technologies].

- The process requires about 400 kg steam of 4 bar [Expert consulted]. The energy in 4 bar saturated steam is about 2749 kJ/kg, which means that 400 kg steam equals 1099 MJ steam. For reference, literature reports a steam use of 1.71 MJ natural gas to produce 1 litre of UCOME compared to 0.93 MJ natural gas to produce FAME [(S&T)2, 2018]. The difference between these values must be in the pre-treatment step, which means that the actual conversion requires 0.93 MJ natural gas per litre of biodiesel. At a boiler efficiency of 85%, this equals 898 MJ steam per tonne of biodiesel. No distillation of glycerine is assumed.

Parameter assumptions
Conversion of pre-treated UCO to UCOME

Item	Unit	Input	Output
Pre-treated UCO	kg	1,000	
Methanol	kg	104.7	
H_2SO_4	kg	20	
KCH_3O	kg	12.6	
KOH	kg	12.8	
Electricity	kWh	50.2	
Steam	MJ	1104	
UCOME	kg		1004
Glycerol	kg		106.1

Conversion of pre-treated UCO to HVO or HEFA

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Parameter assumptions
General considerations on HVO and HEFA

Introduction

- HVO stands for Hydrotreated Vegetable Oils, while HEFA stands for Hydroprocessed Esters and Fatty Acids. The term HVO is used to identify renewable diesel for road transport application, and the term HEFA is used for a type of sustainable aviation fuels.

- From a technical point of view, these terms are confusing, because both product pathways use esters and fatty acids as feedstock, and the terms hydrotreating and hydroprocessing are rather interchangeable and are applicable for reactions in both HVO and HEFA production.

- The production of HVO and HEFA concerns largely the same process. But there are differences. Aviation fuels require shorter hydrocarbons than road diesel and therefore the process requires further cracking, with the drawback that also more co-products are produced. Also, aviation fuels require an additional isomerisation step to improve the cold flow properties. Isomerisation is not needed for HVO (road diesel), but still some producers apply this to improve product quality.

- The terms hydrotreating, hydroprocessing, and also the often used term hydrogenation, actually cover a range of catalytic reactions with hydrogen. For the HVO and HEFA production, the following reactions are the most important:

  - Hydrocracking, both to break the fatty acid chains from the glyceride backbone and to break the long fatty acids into shorter chains.

  - Saturation, to saturate double bonds to become single bonds.

  - Hydrodeoxygenation, to remove oxygen in the form of water.

  - Decarboxylation, to remove oxygen in the form of carbon dioxide.

  - Decarbonylation, which removes oxygen in the form of carbon monoxide and water.

  - Isomerisation of linear hydrocarbon chains into branched hydrocarbons to improve the freezing point of the bio-aviation fuel.

- A schematic overview is given on the next page.

- In the current study, we have focused on saturation, hydrodeoxygenation and isomerisation. Our modelling ignores decarboxylation and decarbonylation as is explained on Page 38. Our focus on hydrodeoxygenation instead increases the yield (good) and the hydrogen consumption (bad) at the same time. Since these impacts somewhat balance each in the cost and carbon footprint calculation, the overall effect on the performance will be limited.

- Details for HEFA are further discussed from Page 40 onwards.

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Main reactions for HVO and HEFA
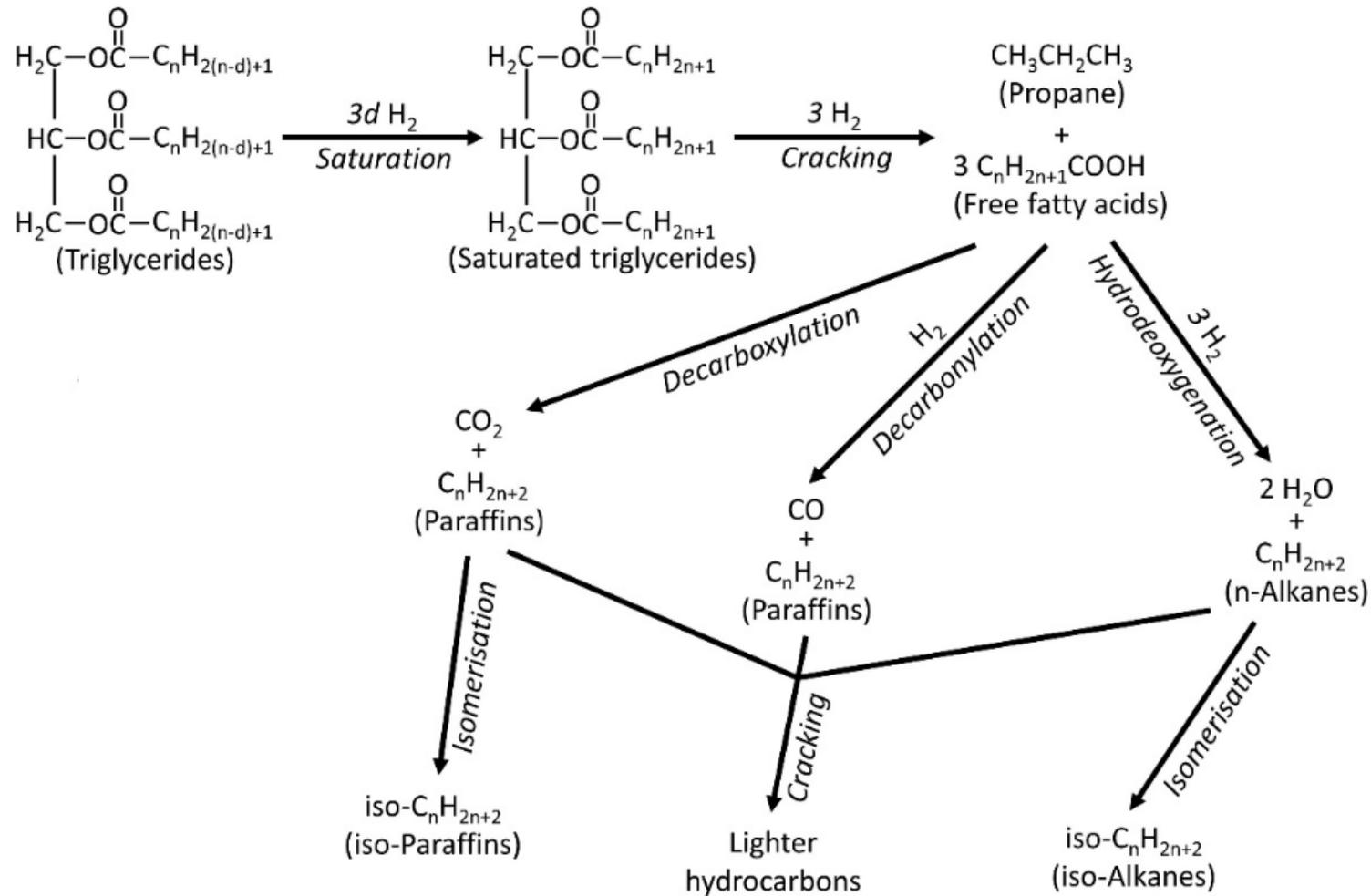
Based on [Doliente SS, Narayan A, Tapia JFD, Samsatli NJ, Zhao, Y and Samsatli S, 2020, Bio-aviation Fuel: A Comprehensive Review and Analysis of the Supply Chain Components]

Parameter assumptions
Conversion of pre-treated UCO to HVO

Mass balance assumptions

- The hydrogen consumption is calculated as followed:
    - Following the scheme on the previous page, esters and fatty acids are first saturated. With on average 1.2 double bonds per fatty acid chain, saturation of the feedstock (with 10% FFA) requires 8.4 kg hydrogen per tonne of feedstock.
    - Then, triglycerides are cracked to yield fatty acids and propane. This requires 6.2 kg per tonne of feedstock.
    - We assume that all the fatty acids are now hydrodeoxygenated, not decarboxylated, or decarbonylated. In reality all these reactions take place with some room for the operator to steer between these reactions. Hydrodeoxygenation gives higher yields of the main product, while the other reactions lead to loss of material via CO_2. So, hydrodeoxygenation is preferred from a feedstock efficiency point of view, but it requires more hydrogen. One cannot have both low hydrogen consumption and a high product yield at the same time. This modelling choice impacts the results, although the higher hydrogen costs in hydrodeoxygenation are spread over more products. The optimal choice to steer for one reaction or the other depends on the costs and revenues which can change over time.
    - The hydrodeoxygenation of all fatty acids requires 19.8 kg
    - We assume that the resulting hydrocarbons are cracked one time (on average) to yield HVO. This requires another 6.6 kg of hydrogen.
    - The total hydrogen consumption is therefore 41 kg per tonne of feedstock, or 49 kg per tonne of product. For comparison, literature reports about 45 kg hydrogen per tonne of product [(S&T)[2] 2018]. This presumably indicates some level of decarboxylation, which, as explained above comes at the cost of a lower product yield.

- When focusing on hydrodeoxygenation, the theoretical maximum main product yield will be 864 kg per tonne feedstock before the final cracking, or 871 kg after cracking (because hydrogen mass is added in the cracking). The loss in mass is completely explained by the deoxygenation (100 kg of oxygen is removed), and propane co-production (about 36 kg).

- In reality, the cracking will yield more propane, at the cost of main product. We have ignored this for the modelling.

- 61.9 kg naphtha (gasoline) and 30.9 kg fuel gas are co-produced per tonne feedstock [(S&T)[2]], and subtracted from the main product.

- Every HVO facility could co-produce some HEFA. This would require further isomerisation and distillation, leading to higher carbon footprint and costs. Therefore, this is not considered here. HEFA production (Page 40) *does consider* HVO co-production since it improves the case.

- The process consumes a small amount of catalyst resulting in a cost of 10 €/tonne product [experts consulted]. However, the mass and cost/unit are not separately known and therefore not included in the table.

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Parameter assumptions
Conversion of pre-treated UCO to HVO

Energy use assumptions

- Energy demand (steam and electricity) are based on literature [(S&T)²]. Often propane and fuel gas are used to produce energy for the installation, which then decrease the natural gas consumption. One cannot have a high propane + fuel gas output and simultaneously have a low natural gas consumption.

- The amount of steam from literature is corrected for the somewhat higher propane output. The energy demand indicated in the table is the remaining external energy demand. Thus steam requires input of natural gas. We assume a boiler with 85% efficiency.

Item	Unit	Input	Output
Pre-treated UCO	kg	1,000	
Hydrogen	kg	41	
Electricity	kWh	85.9	
Steam	MJ	813	
UCO-HVO	kg		778
Propane	kg		36
Naphtha	kg		61.9
Fuel gas	kg		30.9

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Parameter assumptions
Conversion of pre-treated UCO to HEFA

Introduction

- Every HEFA facility co-produces some HVO. When the focus is on optimising efficiency, the HEFA output is below 20%.

- When the focus is on maximum jet production, the HEFA output would be about 55% and HVO about 25%, with with almost 20% of light ends co-produced [ICCT 2019, The cost of supporting alternative jet fuels in the European Union].

Mass balance assumptions

- The hydrogen consumption is calculated in largely the same was as for HVO
  - However, to produce HEFA the hydrocarbons need to be cracked further than HVO. We assume that the later cracking step (centre bottom in Page 37) requires 50% more hydrogen, or 9.9 kg instead of 6.6 kg per tonne product.
  - The product is isomerised over a catalyst. The isomerisation does not require (additional) hydrogen.
  - The total hydrogen consumption therefore becomes 44 kg per tonne of feedstock, or 59 kg per tonne of product (HEFA+HVO). For comparison, literature reports about 45 kg hydrogen per tonne of product [(S&T)2 2018]. This presumably indicates some level of decarboxylation, which, as explained above comes at the cost of a lower product yield.
  - For comparison, other literature estimates the hydrogen consumption to be about 55 kg / tonne product, which is very comparable [Antonissen 2016].

- We have assumed a product slate of 66% HEFA, 15% HVO, 10% naphtha and 9% propane [(S&T)2 combined with expert consulted]. Note that part of the propane results from the glyceride backbone, and part from cracking the hydrocarbon chain. The co-products are unavoidable because of deeper cracking compared to HVO production. This decreases the yield of the main product.

- The combined yield of all four products noted above, can maximally be 92.4% of the feedstock, by weight, when we consider that oxygen is removed (hydrodeoxygenation: 96 kg per tonne feedstock removed) and hydrogen was added (saturation and capping the chains where it was cracked: 20 kg per tonne feedstock inserted).

- Isomerisation does lead to additional catalyst consumption [expert consulted]. However, the amount is unknown, and considering that catalyst is only a small cost, we have assumed the same costs as for HVO production.

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Parameter assumptions
Conversion of pre-treated UCO to HEFA

Energy use assumptions

- The energy demand (steam and electricity) are based on literature [(S&T)[2]]. The electricity consumption is lower than in HVO production (reason unknown), while the steam consumption is considerably higher, because separation of the HEFA from the HVO requires additional distillation.

Item	Unit	Input	Output
Pre-treated UCO	kg	1,000	
Hydrogen	kg	44	
Electricity	kWh	46.5	
Steam	MJ	4,445	
UCO-HEFA	kg		610.0
UCO-HVO	kg		135.7
Propane	kg		84.0
Naphta	kg		93.9

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Co-processing pre-treated UCO with crude oil to diesel

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Parameter assumptions
Co-processing pre-treated UCO with crude oil to renewable diesel

Introduction

- It is possible to co-process lipids, such as UCO with crude oil in traditional crude oil refineries. This can presumably be done up to 5– 10% because of trace metal contaminants (in UCO this would mainly be sodium), and the presence of water and carbon dioxide, which are produced by the removal of oxygen from the feedstock. The limit is furthermore set by the capacity to remove the excess heat from the reactor. The hydrodeoxygenation process is very exothermic and excess heat must be removed. If the reactor temperature increases significantly the catalysts quickly becomes deactivated.

- The investments are presumably lower than for HVO production, see Page 45.

Mass balance assumptions

- In co-processing with crude oil the process cannot be steered as precisely as in a dedicated HVO facility. This would in practice mean somewhat lower production of the main product and more by-product, and also more hydrogen consumption. The higher operating temperatures also steer towards more decarboxylation and decarbonylation, at the cost of product, but also reducing hydrogen consumption. However, we did not find literature that sufficiently specifies these parameters. Therefore, all mass and energy parameters are taken the same as for HVO.

- Consequently, the carbon footprint will be almost the same, as was presented on Page 18 (small difference caused by difference in energy content of the main products).

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Further economic assumptions

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Economic assumptions
Scale and investment costs

- The costs of pre-treatment are taken the same for all four pathways.

- Investment for a typical 100,000 tonne/year UCOME production facility, including all pre-treatment, technology, steel construction, tank farm, and utilities amounts to € 150/t capacity, so the investment of that plant would be 15 M€ in total [expert consulted].

- A 500 ktonne/year HVO production facility has a capital cost of 550 M€, or about 0.86 €/l [(S&T)2]. Expert consultation suggests that the capital costs are about 5 USD/gallon installed capacity or up to 700 M€ for the same 500 ktonne/year facility [expert consulted] .

- The investment costs for HEFA production facility range from 0.57 to 1.84 €/l according to literature [(S&T)2]. This equals 740 to 2390 €/tonne installed capacity. Also experts consulted differed in opinion, with indications as 6 USD/gallon and 25% higher than HVO facilities [expert consulted]. We have assumed an investment halfway the range indicated by (S&T)2: 1.21 €/l, or 1,565 €/tonne

- There is limited information about the investment costs of co-processing. Still, the costs are assumed to be considerable, because of required infrastructure, feedstock reception, storage, feeding to reactor, other equipment. We have assumed these to be half of HVO investment (greenfield factor as suggested by S&T2)

- Furthermore, an interest rate of 10% is assumed and a depreciation time of 10 years.

Item	Capacity	Investment
Pre-treatment	90 M litre pre-treated UCO/year	4 M€
UCOME production	100 ktonne UCOME/year	15 M€
UCO-HVO production	500 ktonne HVO/year	600 M€
UCO-HEFA production	400 ktonne HEFA+HVO/year	626 M€
Co-processing UCO in refinery	500 ktonne diesel	300 M€

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Economic assumptions
Other costs

- Only major cost factors are noted below

- The UCO costs are the main factor in cost calculations. The cost of UCO fluctuates considerably in time. Note that the fuel production costs of all four pathways move up and down with the UCO costs.

Item	Cost	
UCO	840 €/tonne	
Methanol	313 €/tonne	
Hydrogen	1200 €/tonne	For grey hydrogen
Catalyst cost for UCOME	12.5 €/tonne fuel	
Catalyst cost for UCO to HVO/HEFA/co-processed	10 €/tonne fuel	
Electricity	0.18 €/kWh	
Steam	0.0055 €/MJ	

Carbon footprint assumptions

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Carbon footprint assumptions
Method and factors

- Method of RED II Annex V has been applied. Co-products are accounted via energy allocation.

- Impact factors for materials and energy consumed in the processes have been taken from Biograce v4

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