A carbon footprint of HVO biopropane

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Abstract: Biopropane made by hydrogenating vegetable or animal oil/fat is being commercialized as a biofuel alternative to liquefied petroleum gas (LPG). Its carbon footprint has been calculated from field to tank, using public data for each process in the supply chain, for six main feedstocks: palm oil, palm oil fatty acid distillate, tallow, used cooking oil, rape oil, and soy oil. Scenarios have been applied to the calculations using four main variables: allocation method, i.e., economic or energy; methane capture at the oil mill (or not); application of indirect land-use change (or not); and classification of the feedstock as a residue (or not). HVO biopropane’s carbon footprint varies, depending on the feedstock and the four variables, from as low as 5 g CO₂e/MJ to as high as 102 g. In most cases, this qualifies for government support, i.e., financial credits and biofuel mandates enacted by EU member states under the Renewable Energy Directive. © 2017 The Authors. Biofuels, Bioproducts and Biorefining published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Supporting information may be found in the online version of this article.

Keywords: biopropane; bioLPG; carbon footprint; renewable diesel; HVO biodiesel

Introduction

HVO biopropane, unavoidably created in the production of renewable diesel from oils and fats, is the newest commercially-available biofuel. It is a drop-in fuel, i.e., chemically identical to fossil propane, and so can substitute fossil propane entirely.¹

Research on the HVO process* dates back about 30 years, and full-scale production ensued about a decade ago. Today there are about ten sites producing an estimated 3.5 million tonnes per year of renewable diesel. Also known as HVO biodiesel, HEFA diesel, HDRD, and Green diesel,² renewable diesel is sold primarily into road-transport and aviation markets. Most HVO biopropane produced at these plants is not recovered as a fungible product. It is left in a mixture of off-gases – anything that is not diesel – which are consumed as low-value fuel gas.

This changes in 2017, when Finland-headquartered Neste begins extracting HVO biopropane from its HVO plant in Rotterdam, NL. The company expects to sell 30 000 to 40 000 tonnes per year of the product. The first four years of output have been committed to SHV Energy, which will sell HVO biopropane as a biosubstitute for fossil liquefied petroleum gas (LPG), much in the same way biodiesel substitutes fossil diesel and bioethanol substitutes gasoline.

What are HVO biopropane and renewable diesel?

Natural fats and oils are triglycerides. Three long-chain hydrocarbons are bound to a 3-carbon backbone by ester links. The HVO process breaks these links, by adding hydrogen to convert the ester’s oxygen to water, which cleaves one molecule of triglyceride into three molecules of long-chain hydrocarbon, typically around 16–18 carbons, plus one molecule of propane (C₃H₈).

The typical, theoretical equation can be written as:

\[ \text{C}_{57}\text{H}_{104}\text{O}_6 + 12 \text{H}_2 \rightarrow \text{C}_{17}\text{H}_{36} + 2 \text{C}_{18}\text{H}_{38} + \text{CO}_2 + 4 \text{H}_2\text{O} + \text{C}_3\text{H}_8 \]

(1)

Rotterdam, NL. The company expects to sell 30 000 to 40 000 tonnes per year of the product. The first four years of output have been committed to SHV Energy, which will sell HVO biopropane as a biosubstitute for fossil liquefied petroleum gas (LPG), much in the same way biodiesel substitutes fossil diesel and bioethanol substitutes gasoline.

*HVO is the abbreviation for hydrogenated vegetable oil. Some analysts call it the hydrogenation (HD) process.
In practice, some fats/oils require more hydrogen, because they have some unsaturated carbon bonds (i.e., double bonds) that are converted to saturates (single bonds). The molar fractions of biodiesel, carbon dioxide, and water coming out can vary slightly, depending on how the esters are cleaved. Some of the biodiesel is reformed to a mixture of shorter-chain hydrocarbons, often referred to as bio naphtha. The biopropane and biopropane are unavoidable byproducts to the process.

Production of HVO biopropane

Global capacity for HVO biopropane is believed to be around 220 000 tonnes annually, albeit, not all capacity is currently operating (Table 1). According to a UK Department of Energy & Climate Change report, the plant in Geismar, LA, USA, did extract and sell biopropane when it was owned and operated by Dynamic Fuels, but this appears to have ceased. The current owner/operator’s website says biopropane is sold as a bionaphtha mixture.

HVO biopropane supply chain, by process

From public data sources, a footprint-relevant definition of the HVO biopropane supply chain was developed, from a search and analysis of both the peer-reviewed and grey literature. The system was defined into five process steps (or life-cycle phases): oil/fat supply, hydrogen production and transport, HVO process, biopropane extraction and purification, biopropane transport.

Oil/fat supply

Oils and fats for HVO processing can be made on purpose, and they can also arise as residues or wastes of other processes.

On-purpose feedstocks

The primary feedstocks currently used to make biodiesel (renewable diesel or FAME) in Europe have been inventoried for this study: crude palm oil, rapeseed oil, and soybean oil. Crude palm oil is produced on plantations, mainly in Southeast Asia. Fruit bunches (FBs) are harvested from palm trees. These are crushed to extract the palm oil, and the palm kernels are also crushed to make palm-kernel oil and palm-kernel cake. Rapeseed is produced on farms, mainly in Europe but also in Canada. Seeds and straw are harvested. The seeds are crushed to extract oil and rapeseed cake. Soybeans are produced on farms, mainly in Brazil and the USA. The beans are crushed to extract oil and soya cake.

Mass/energy/emissions inventories for these three oils were compiled (Supplemental Material, Tables S1–S3), based on careful examination of the following sources: for palm oil, for rape oil, and for soy oil. A nitrous oxide emission in a report from Argonne Labs was not included, because it was an order-of-magnitude out from the other estimates. Where these sources diverged, their figures were averaged.

| Table 1. HVO biopropane producers. |
|-----------------------------------|
| **Owner/Operator** | **Location** | **Startup year** | **Capacity kt/y** | **Is biopropane extracted?** | **Status** |
| BP | Bulwer Island, AUS | 2007 | 3 | No | Shut down |
| ConocoPhillips | Whitegate, IR | 2006 | 5 | No | |
| Diamond Green Diesel | Norco, LA, USA | 2013 | 10 | No | |
| Eni | Porto Marghera, I | 2014 | 20 | Reportedly yes | |
| Hitachi Zosen | Kyoto, J | 2004 | Negligible | No | |
| Neste | Porvoo, SF | 2007 | 2 x 5 | No | |
| | Rotterdam, NL | | 30–40 | As of 2017 | |
| | Singapore | | 30–40 | No | |
| Petrobras | 4 refineries in Brazil | 2007 | 4 x 6 | No | Reportedly shut down |
| Renewable Energy Group | Geismar, LA, USA | 2010 | 20 | Not as such. It is sold in a mixture called ‘renewable naphtha’. |
| Total | La Mède | 2017 | 55 | Reportedly planned | |
| UPM | Lappeenranta, SF | 2015 | 6 | No | |

Sources: UK Department of Energy & Climate Change, Yano J et al. Purchased in 2014 from Dynamic Fuels, which was a joint-venture of Tyson Foods and Systrene.
Several points in the inventories merit further explanation:

- No direct land-use change was assumed, because the farms are presumed to have been in operation before 2008. According to European Union rules, all plantations already operating before January 1, 2008 are ‘grandfathered’ in as not creating land-use change.
- Steam and electricity at the palm-fruit-bunch crushing plant are supplied by a combined heat/power (CHP) unit run on empty fruit bunches (EFBs), fiber, and shell from the harvest. This is considered as a closed, internal loop.
- Some 10–15% of the EFB is recycled as compost to the plantation. Again, this is considered a closed, internal loop.
- Economic value of the crush products is an average of the three sources who calculated it.4,6,7
- Palm-oil mill effluent (POME) treatment – at some palm-oil mills, the organic-laden, aqueous effluent is usually charged to a wastewater lagoon. The economic-allocation case assumes that the methane arising from this lagoon (from anaerobic degradation, i.e., rotting, of the organics), is not captured, that it is released to the atmosphere.
- Indirect land-use change (iLUC) has been considered in one of the footprint scenarios. In this case, iLUC factors proposed under the Renewable Energy Directive (Supplemental Material, Table S10), 55 g CO₂e/MJ for oil-based biodiesels, have been applied to the on-purpose oils.

Waste/residue feedstocks

The primary wastes/residues used to make HVO biodiesel in Europe have been inventoried for this study: Palm fatty acid distillate (PFAD), tallow and used cooking oil (UCO). (These are less used to make FAME biodiesel, because they are mostly unsuitable to the FAME process.)

PFAD is a mixture of fatty acids that are distilled from crude palm oil to make refined palm oil. PFAD is uneconomical for humans, but it can be digested by animals, and it can be used as a feedstock for soaps and some chemicals. Tallow comes from animals raised for food, such as cattle, pigs, and chickens. These are sent to abattoirs, where they are slaughtered and butchered into meat and (sometimes) hides. This amounts to about 40–70% of the animal weight. (With fish, the edible portion is reportedly much lower.) The remaining animal carcass is sent to a renderer, which converts it to protein meal and tallow (fat). UCO, often called yellow grease in the USA and sometimes called waste cooking oil, is collected from commercial food-frying operations.

Mass/energy/emissions inventories were compiled (Supplemental Material, Tables S4 and S5), based on careful examination of sources for PFAD and tallow.6,7,10–21

PFAD is classified as residue or waste by Finland, Norway, Sweden, Italy, and the US federal government.23 It is classified as a product by the UK. Classification as a residue is also possible, because as reported by Cheah et al.24 and other market analyses, PFAD consistently trades at prices less than those of its feedstock, crude palm oil. UCO is classified by the UK Department for Transport 14 as a waste. Another study for the same UK Department of Transport argues that UCO is a waste, yet presents a raft of evidence that it has economic value. A study by SRI Consulting clearly classifies UCO as a product, and allocates some of the burden of oil production (cultivation and processing) to the UCO.

In this study, the same approach was taken as SRF’s: We have allocated by economic value of the fresh and the used grease. According to a 40-year time series generated by the US Energy Information Administration, this is typically about 2:1, i.e., by weight fresh grease sells for about double the price of used. So, in principle, 66.7% of the inputs/outputs would be allocated to fresh grease, while 33.3% would be allocated to yellow grease (UCO). Because only an estimated 70% of fresh grease is recycled as UCO, we adjusted our actual allocation proportionately to 75:25.7

Hydrogen production (and transport)

Most commercial hydrogen comes either from an oil refinery or from a natural gas reformer. Refineries are also major consumers of hydrogen, so the incremental supply source will almost always be a reformer. These react steam and methane (natural gas) to create hydrogen, which creates carbon dioxide as a waste.

The theoretical reaction is

\[ \text{CH}_4 + 2\text{H}_2\text{O} \rightarrow \text{CO}_2 + 4\text{H}_2 \]  

which yields 1 kg of hydrogen for every 2 kg of methane feedstock. In practice, more methane is needed, some as fuel and because the reaction is not 100% efficient.

A mass/emissions inventory for animal fat production was compiled (Supplemental Material, Table S6), based on careful examination of sources.7,26–31 A report by Foster Wheeler, Decarbonisation of Fossil Fuels; Report Nr. PH2/2, prepared for the Executive Committee of the IEA Greenhouse Gas R&D Programme in March 1996 was also used.

† This is a secondary reference – i.e., the figures have been quoted in other sources.
HVO process

In the HVO process, a triglyceride vegetable (or animal) oil is reacted with hydrogen to create an aliphatic hydrocarbon of around C16–C18 in length, i.e., renewable diesel. The reaction creates other outputs: carbon dioxide, water, and a mixture of shorter hydrocarbons, including propane.

There are two main reactions that can happen in the HVO process:

\[
C_n\text{-COOH} + 0.5 \text{H}_2 \rightarrow C_n + \text{CO}_2 \quad \text{decarboxylation (DCO)} \tag{3}
\]

\[
C_n\text{-COOH} + 3 \text{H}_2 \rightarrow C_{n-1} + 2 \text{H}_2\text{O} \quad \text{hydrodeoxygenation (HDO)} \tag{4}
\]

By adjusting process conditions and the catalyst, one reaction can be favored over the other, although there will always be some mixture of the two.\(^{32}\) Favoring DCO or HDO changes the composition of the outputs considerably. The theoretical outputs for a feedstock of brown grease\(^{33}\) are:

- DCO – 15.5 weight % CO\(_2\)
- HDO – 12.7 weight % H\(_2\)O

Whichever one is favored, hydrogen inputs will be greater when the feedstock oil is more unsaturated, because hydrogen is consumed to saturate the olefinic carbon bonds.

A mass/emissions inventory for the HVO process was compiled (Supplemental Material, Table S7), based on careful examination of sources.\(^{3,4,6–9,15,18,19,30,32,34–37}\)

Allocation for the HVO process is, in most of the existing studies, not mentioned. Reports from both SRI Consulting\(^7\) and Argonne\(^9\) avoid allocation by giving the crude biopropane an avoided product credit. Argonne\(^9\) also reports percentages for market, energy, and hybrid allocations. Argonne’s percentages are different to those calculated in this study (Supplemental Material, Table S8). Article 2 of the EU’s Renewable Energy Directive,\(^10\) as amended on September 9, 2015, offers another allocation alternative: classifying the HVO crude biopropane as a processing residue, i.e., ‘a substance that is not the end product(s) that a production process directly seeks to produce; it is not a primary aim of the production process and the process has not been deliberately modified to produce it’.

Biopropane extraction and purification

The HVO process generates a liquid phase of renewable diesel plus a light-ends fraction, a mixture by weight of about 70% crude HVO biopropane and 30% HVO bio naphtha. To be sold as substitute LPG, the biopropane must be extracted and purified to an LPG specification.

A mass/emissions inventory for the extraction and purification was compiled (Supplemental Material, Table S9), based on careful examination of the following sources that serve as proxies for the process:\(^{4,38–42}\)

Biopropane transport

HVO biopropane must then be stored and transported to consumers. Most of the existing studies of renewable diesel do not report these details explicitly. The exception is Nikander,\(^30\) who assumes that renewable diesel is transported 200 km by a 39-t truck to a blending site. At the largest HVO extraction site (Table 1), Rotterdam, an LPG jetty for loading barges and ships will be located directly adjacent to the plane. So, the base case for this study is to assume ship transport to local storage in Rotterdam, Europe’s largest concentration of refined product production and storage.

Footprint method

The footprints in this study were calculated according to prevailing practice and convention.

Only public sources of data were used. They have been cited in the text and listed in the references.

The reference flow of this study is that of HVO biopropane and its preceding supply chain. This paper details the field-to-tank supply chain, from its origins in agriculture through to storage of the finished product. In the tank-to-wheel part, no carbon footprint is registered, because the carbon in the biopropane is bio-based and in this instance carbon neutral. The functional unit is the physical quantity of HVO biopropane. This is the unit by which LPG is sold, and by which HVO biopropane will most likely be sold as well. Physical quantity of LPG or propane is typically denominated in mass (kg or tonne), volume (usually liters, sometimes cubic meters or even barrels) or energy content (MJ at lower heating value). For biopropane, the energy density is assumed to be equal to that of fossil propane, 46.296 MJ LHV/kg.\(^{43}\) In this study, we mostly use MJ (at LHV), because this is the unit used most commonly for biofuels, and it is definitely used by the EU and its member states.

The footprints were calculated in SimaPro, Version 8.0.5.13, and further manipulated in Excel. The life-cycle model was built using the inputs described in the section on

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\(^{\text{No actual units have yet been operated that do this process at commercial scale. So, the figures have been estimated from other, similar processes.}}\)
the HVO biopropane supply chain, by process. Minor inputs and energy emissions were taken from SimaPro libraries, mainly that of ecoinvent. The model was calibrated with a calculation for renewable diesel, which can be compared to other estimates. Then scenarios were run for biopropane.

Results and discussion: biopropane footprint

First the model was calibrated by calculating a footprint for Renewable Diesel. Then it was run for HVO biopropane for all feedstocks under all scenarios. The scenarios were chosen to represent the range of constraints that might apply to suppliers and regulators in estimating footprints:

- Economic allocation
- Energy allocation
- Energy allocation, with methane capture (at the palm oil mill)
- Energy allocation, with methane capture and iLUC
- Economic allocation, feedstock is residue (as defined by the Renewable Energy Directive)
- Energy allocation, feedstock is residue

Calibration of the footprint model

Run for palm oil feedstock to produce Renewable Diesel, the model generates a footprint of 40 g CO₂/MJ (Table 2). Its major constituents are: methane from the rotting of the palm oil mill effluent (POME); carbon dioxide from hydrogen and nitrogen-fertilizer production (gas-intensive processes); carbon dioxide from operations of the palm oil plantation (mostly diesel emissions from power equipment); and ship emissions from the transport from Malaysia (or Indonesia) to an HVO plant in Europe (Rotterdam).

This result falls in the lower end of ‘official’ estimates, which range from 39 to 50 g CO₂/MJ. Official means footprints published by government regulators (Table 3): the European Commission in the Renewable Energy Directive and in BioGrace; and the US EPA. For further reference, a figure is also included from the first public study in this area, which was conducted by the author.7

There are other estimates outside of the official range. For instance, a study by ecoinvent estimates a footprint of 42 g CO₂/MJ for palm oil only (which would presumably lead to a renewable diesel footprint of over 50). A more recent study by Blonk estimates the palm oil footprint at 241 g CO₂/MJ. This probably includes a large iLUC factor and appears to be much broader than a footprint estimated by conventional methods.

HVO biopropane from palm oil

Using the calibrated footprint model, the footprint was calculated for HVO biopropane using economic allocation (Table 4), which comes out at 16 g CO₂/MJ. This is the first precise, public estimate of HVO biopropane’s footprint. A study for the UK government estimated a range of 10–50 CO₂/MJ, but did not stipulate a specific base case.
Under alternate scenarios, the HVO biopropane (and biodiesel) footprints vary considerably (Table 5). Changing from economic allocation to energy allocation adds nearly 16 g to the biopropane footprint, and slightly decreases that of biodiesel. This also slightly changes the footprint at the oil mill. Adding methane capture sinks the footprint by nearly 7 g.

Then there is the question of iLUC. In Annexes V and VIII of the December 17, 2012 Amendment of the EU Renewable Energy Directive and the Fuel Quality Directive (pp 19–21), an iLUC factor of 55 CO₂/MJ is proposed for ‘oil crops’. This has been applied to biopropane and renewable diesel (Table 5). Whether iLUC should be included, and if so, what its factors should be, are still very much open questions. As supplemental research to this study shows (Supplemental Material, Table S10), currently proposed factors for palm oil range from 44 to 231 CO₂/MJ.

Two other scenarios were not considered, because they are theoretical. One is that crude HVO biopropane be classified as a residue. This is plausible, in that glycerine from FAME biodiesel production is classified under RED as a residue, and its production is very similar to that of HVO biopropane (i.e., it is an unavoidable byproduct of biodiesel synthesis). However, the UK Government has explicitly rejected this classification, ruling that HVO biopropane is a co-product, not a residue. If crude HVO biopropane were classified as a residue, the HVO biopropane footprint would be about 8 CO₂/MJ. Also not considered was the scenario that palm oil could be classified as a waste or residue.

### Waste/residue feedstocks: PFAD, tallow, and UCO

In addition to palm oil, these three raw materials are leading sources of feedstock for Renewable Diesel and HVO biopropane.

For PFAD (Table 6), in the economic-allocation case, the footprint comes out at 15 g CO₂/MJ, and its major constituents (obviously) are the same as those for HVO biodiesel. Under the scenarios, its footprint ranges from 5 to 80 g CO₂/MJ.

For tallow (Table 7), in the economic-allocation case, the footprint comes out at 17 g CO₂/MJ. Its major constituents are production of the tallow (which is relatively energy intensive) and the HVO process.

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Personal communication with the Department for Transport.
If tallow is classified as a residue, the footprint drops considerably. With economic allocation, it falls to 5 g, whereas with energy allocation the footprint is 11 g (Table 8). The other scenarios applied to palm are not applicable: there is no methane-capture option in tallow production, and iLUC does not apply.

For UCO, the oil that went into the fryer is assumed to be rape oil, which is a common frying oil in Europe. In the economic-allocation case, the UCO footprint comes out at 9 g CO$_2$/MJ (Table 9). Its major constituents are hydrogen production, rapeseed cultivation, nitrogen fertilizer production and steam (in the HVO plant and the oil mill).

If UCO is classified as a residue, the footprint drops to 5 g with economic allocation, and it falls to 11 with energy allocation (Table 10). If iLUC were applied to UCO, the figure of course would rise.

### The other main feedstocks: rape and soy oils

Neither rape nor soy oil are expected to be primary feedstocks in European biopropane production. Still, these are significant feedstocks in global production of biodiesel, so their footprints are worth knowing, at least as benchmarks.

Rape oil, in the economic-allocation case, has a footprint of 19 g CO$_2$/MJ (Table 11). Its major constituents are production of rapeseed, nitrogen-fertilizer production and the HVO process. If allocation is done by energy rather than economic value, the footprint rises to 47 g. If on top of that, an iLUC factor is added, the footprint climbs to 102 g (Table 12).

Soy oil, in the economic-allocation case, has a footprint of 17 g CO$_2$/MJ (Table 13). Its major constituents are cultivation of soybeans, hydrogen production and the HVO process. If allocation is done by energy rather than economic value, the footprint rises to 47 g. If on top of that, an iLUC factor is added, the footprint climbs to 102 g (Table 12).

### Tables

**Table 8. HVO footprints, tallow, under primary alternative scenarios, g CO$_2$/MJ.**

| Scenario                                      | Biopropane Sum |
|-----------------------------------------------|----------------|
| Economic-allocation case                      | 16.6           |
| Economic, feedstock is residue                | 5.2            |
| Feedstock is residue, with energy allocation at HVO and mill | 11.1 |

**Table 9. HVO biopropane footprint, UCO, economic-allocation case, by major contribution.**

| Process                                     | g CO$_2$/MJ |
|---------------------------------------------|-------------|
| SUM                                         | 9.3         |
| UCO, at collection                          | 3.7         |
| Transport                                   | 0.2         |
| HVO process, oil-to-product                 | 3.9         |
| Purification, storage                       | 1.4         |

**Table 10. HVO footprints, UCO, under primary alternative scenarios, g CO$_2$/MJ.**

| Scenario                                      | Biopropane Sum |
|-----------------------------------------------|----------------|
| Economic allocation                           | 9.3            |
| Economic allocation, feedstock is residue     | 5.2            |
| Feedstock is residue, with energy allocation at HVO and mill | 11.1 |
| Energy allocation, with iLUC$^a$             | 34.6           |

$^a$Highly uncertain – this should be considered a rough estimate.

**Table 11. HVO biopropane footprint, rapeseed, economic-allocation case, by major contribution.**

| Process                                     | g CO$_2$/MJ |
|---------------------------------------------|-------------|
| SUM                                         | 19.4        |
| Rape oil, crude, cultivation and milling     | 14.1        |
| Transport                                   | 0.1         |
| HVO process, oil-to-product                 | 3.8         |
| Purification, storage                       | 1.4         |

**Table 12. HVO biopropane footprints, rape oil, under primary alternative scenarios, g CO$_2$/MJ.**

| Scenario                                      | Biopropane Sum |
|-----------------------------------------------|----------------|
| Economic allocation                           | 19.4           |
| with energy allocation, HVO and oil mill      | 47.4           |
| With energy allocation, with iLUC$^a$         | 102.4          |

$^a$As proposed under the EU Renewable Energy Directive.

**Table 13. HVO biopropane footprint, soy, economic-allocation case, by major contribution.**

| Process                                     | g CO$_2$/MJ |
|---------------------------------------------|-------------|
| SUM                                         | 16.7        |
| Soy oil, crude, cultivation and milling      | 11.3        |
| Transport                                   | 0.1         |
| HVO process, oil-to-product                 | 3.8         |
| Purification, storage                       | 1.4         |
value, the footprint rises to 40 g. If on top of that, an iLUC factor is added, the footprint climbs to 95 g (Table 14).

**Conclusion: Biopropane’s footprint generally low, but scenarios vary it**

Seen as a whole, HVO biopropane’s footprint by feedstock and scenario (Table 15) varies considerably, but in most cases, it qualifies for government support, i.e., financial credits and biofuel mandates enacted by EU member states under the Renewable Energy Directive (Table 16).

This variability of footprints, according to footprint-calculation method, has clear precedents: for instance in a study of forklifts and one of forest products. This potential variability should be kept in mind by footprint users: regulators, suppliers, and consumers.

### Table 14. HVO biopropane footprints, soy oil, under primary alternative scenarios, g CO₂/MJ.

| Scenario                  | Biopropane Sum |
|---------------------------|----------------|
| Economic-allocation case  | 16.7           |
| Energy allocation, HVO and oil mill | 40.4         |
| Energy allocation, with iLUC | 95.4           |

aAs proposed under the EU Renewable Energy Directive.

### Table 15. HVO biopropane footprints, by scenario and feedstock, g CO₂/MJ (LHV).

| Scenario                  | Feedstock  |
|---------------------------|------------|
| Economic allocation       | Palm | PFAD | Tallow | UCO | Rape | Soy | Total |
|                           | 16.2 | 15.0 | 16.6  | 9.3 | 19.4 | 16.7 |        |
| Energy allocation         | 39.4 | 36.3 | 40.4  | 20.9| 47.4 | 40.4 |        |
| Energy allocation, with methane capture | 26.2 | 24.8 | NA    | NA  | NA   | NA   |        |
| Energy allocation, with methane capture and iLUC | 81.2 | 79.8 | NA    | 34.6| 102.4| 95.4 |        |
| Economic allocation, feedstock is residue | NA  | 5.2  | 5.2   | 5.2 | NA   | NA   |        |
| Energy allocation, feedstock is residue | NA  | 11.1 | 11.1  | 11.1| NA   | NA   |        |

### Table 16. EU qualification limits for HVO biopropane, g CO₂e/MJ (LHV).

| Biofuel (transport) | 100% | 50% |
|---------------------|------|-----|
| Biofuel (transport) | 83.8 | 41.9|
| Biofuel (transport) | 77   | 38.5|
| Biofuel (transport) | 91   | 45.5|
| Biofuel (transport) | 85   | 42.5|

 electric and cogeneration are unlikely to be applications of biopropane, but are included for reference.

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