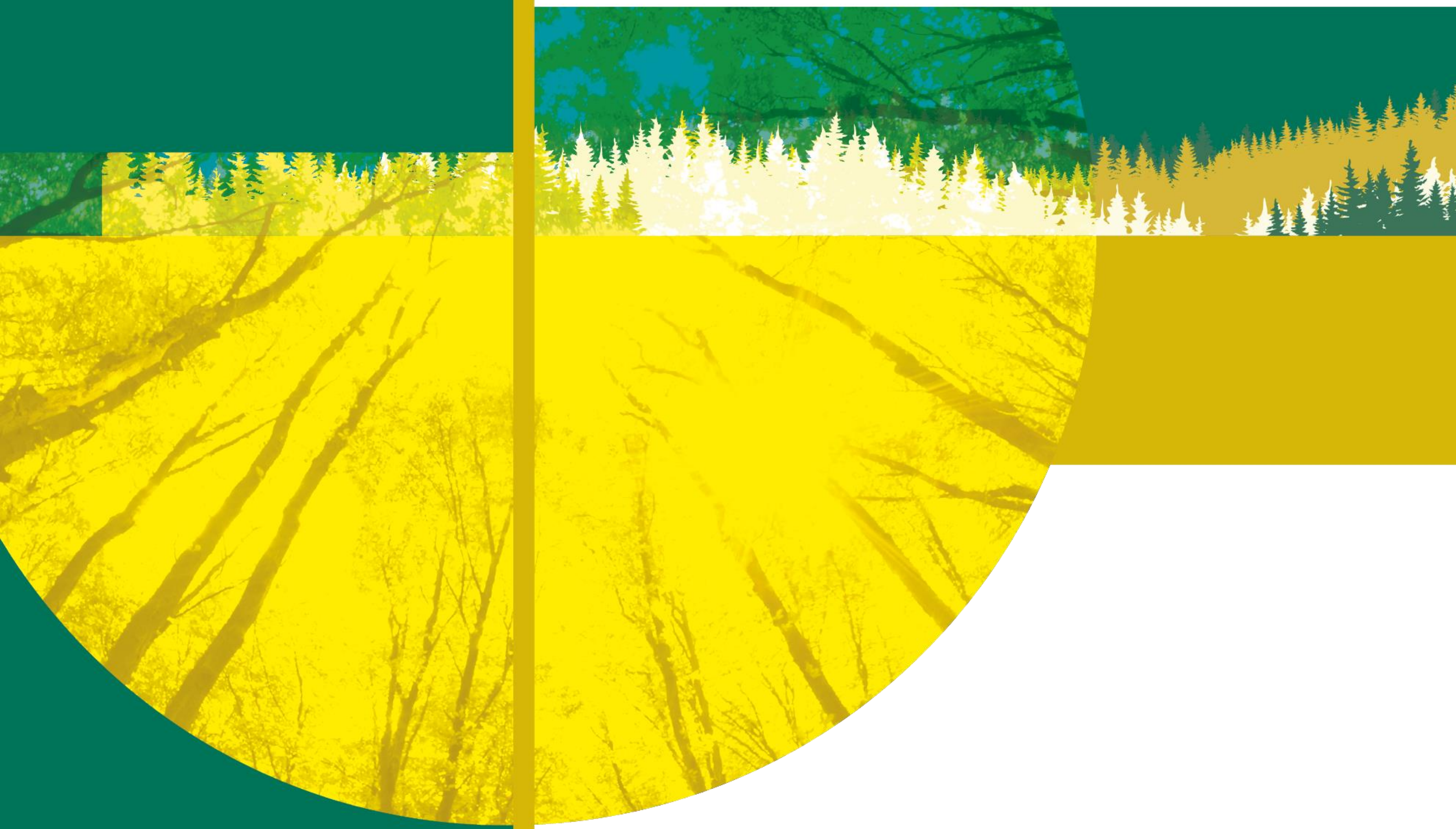
Technical Report

Comparison of Biofuel Life Cycle Analysis Tools

Phase 2, Part 1: FAME and HVO/HEFA



IEA Bioenergy

IEA Bioenergy: Task 39: December 2018

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Prepared by

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Published by IEA Bioenergy

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Task 39 – Commercializing Liquid Biofuels

International Energy Agency (IEA Bioenergy)

December 2018

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Abbreviations

2G: second-generation ethanol
BTL: biomass-to-liquid
CORSIA: Carbon Offsetting and Reduction Scheme for International Aviation
EU: European Union
FAME: fatty acid methyl esters
FFA: free fatty acid
FFB: fresh fruit bunches
GHG: greenhouse gases
GWP: global warming potential
HEFA: hydroprocessed esters and fatty acids
HHD: heavy heavy-duty truck
HRD: hydrotreated renewable diesel
HRG: hydrotreated renewable gasoline
HRJ: hydrotreated renewable jet fuel
HVO: hydrotreated vegetable oil
LCA: Life Cycle Analysis
LMC: land management change
LPG: light petroleum gas
LUC: land use change
MHD: medium heavy-duty truck
POME: palm oil mill effluent
NExBTL: Neste renewable diesel
NG: natural gas
UCO: used cooking oil
USA: United States of America
VSB: Virtual Sugarcane Biorefinery

Contents

Executive summary

Bioenergy plays an important role in the decarbonization of the transportation sector. Its medium and long-term benefits depend on the reduction of greenhouse gases (GHG) emissions brought forth by the conversion of renewable feedstocks, which can be quantitatively determined through a Life Cycle Analysis (LCA) methodology. In this context, identifying the main differences and commonalities in methodological structures, calculation procedures and assumptions of different LCA models are desired to demonstrate the possibility of obtaining homogeneous results for similar production chains. This report presents the main results of the study carried out for Phase 2 of the project entitled "Comparison of Biofuel Life Cycle Assessment Tools", which is included in the activities of Task 39 (Commercializing Liquid Biofuels from Biomass) of the International Energy Agency Bioenergy Technology Collaboration Program (IEA Bioenergy).

The scope of this study is restricted to biofuels employed for transportation by road (biodiesel or FAME, Fatty Acid Methyl Esters) and air (biojet fuel or HVO/HEFA, Hydrotreated Vegetable Oil/Hydroprocessed Esters and Fatty Acids) produced from either soybean oil, palm oil and used cooking oil (UCO). Five models were considered in the study:

- BioGrace (European Community): available in https://biograce.net/home;
- GHGenius (Canada): available in https://www.ghgenius.ca/index.php/downloads;
- GREET (United States of America): available in: https://greet.es.anl.gov/index.php?content=greetdotnet;
- New EC (European Community): available in http://data.jrc.ec.europa.eu/dataset/jrc-alf-bio-biofuels_jrc_annexv_com2016-767_v1_july17;
- Virtual Sugarcane Biorefinery - VSB (Brazil): not available to external users.

While four models are publicly available and serve regulatory purposes (BioGrace/GHGenius/GREET/New EC), the VSB was initially developed by CTBE/CNPEM to assess the sugarcane production chain, having further expanded its scope to several other feedstocks and conversion pathways within a biorefinery context. The

BioGrace model, although released in 2015, still uses 2008 input data; the new JRC dataset from 2017 (and used in this study under the designation "New EC") is freely available online. The results presented in this report are limited to the GHG emissions determined by each model with the default conditions to which they were developed using both cradle-to-gate and cradle-to-pump boundaries. The cradle-to-gate approach considers the emissions of biofuel production from the feedstock production up to the gate of the biofuel producing unit, while the cradle-to-pump analysis includes additional impacts of biofuel distribution to fuel pumps.

Table ES1 presents a summarizing matrix with the default feedstock/technology duos in each model considered in this study.

Table ES1: Model – pathway matrix

	BioGrace	**GHGenius**	**GREET**	**New EC**	**VSB**
Soybean FAME	yes	yes	yes	yes	yes
Soybean HVO/HEFA	created[1]	yes	yes	yes	yes
Palm FAME	yes	yes	created[1]	yes	yes
Palm HVO/HEFA	yes	yes	yes	yes	yes
UCO FAME	yes	yes	no[2]	yes	yes
UCO HVO/HEFA	created[1]	yes	no[2]	yes	yes

[1] This means the model does not have the pathway as default. For instance, in the case of soybean HVO/HEFA in BioGrace, the pathway was created considering default data for soybean cultivation and oil extraction, and default data for hydrogenation of palm oil. The same reasoning was applied in the other two cases.
[2] GREET does not have a default process for UCO collection and transportation.

Table ES2 summarizes the total GHG emissions for the five assessed models and the six assessed pathways considered in this study. Results for the New EC model refer to new data (2017) supplied by JRC (agricultural and industrial inputs, transport distances and efficiencies, and emission factors) inserted in the BioGrace calculation tool.

Table ES2: Summary of cradle-to-pump emissions in g CO_2eq/MJ biofuel

	BioGrace	GHGenius	GREET	New EC	VSB	Δ GHG emissions[1]
Soybean FAME	**56.94**	**16.90**	34.47	42.27	25.03	***40.04***
Soybean HVO/HEFA	**50.63**	48.58	47.57	41.94	**25.46**	***25.17***
Palm FAME[2]	65.96	**78.21**	**24.15**	57.97	30.78	***54.06***
Palm FAME[3]	**36.94**	-	-	**42.23**	-	***5.29***
Palm HVO/HEFA[2]	58.90	**99.06**	37.54	55.99	**31.57**	***67.49***
Palm HVO/HEFA[3]	**28.97**	-	-	**39.63**	-	***10.66***
UCO FAME	**21.27**	**2.99**	-	17.28	4.86	***18.28***
UCO HVO/HEFA	**11.64**	**-14.85**	-	10.71	4.15	***26.49***

Red cells represent the highest emissions among models, while green cells indicate the lowest ones

[1] Difference between the highest and lowest emission

[2] Does not include CH_4 capture from palm oil mill effluent (POME)

[3] Includes CH_4 capture from palm oil mill effluent (POME)

BioGrace estimates the highest emissions in soybean and UCO pathways. GHGenius also estimates the lowest GHG emissions for three pathways: UCO biofuels and soybean FAME. VSB follows with HVO/HEFA from soybean and palm and GREET has the lowest emissions only for palm FAME. Palm biofuels can also be assessed in two variants: with or without the capture of CH_4 from palm oil mill effluent. This option is only taken into account by BioGrace and New EC, both of which clearly demonstrate the impact in carrying out this additional operation associated to palm oil extraction.

Regarding the comparison of models and pathways, the most discrepant results for FAME and HVO/HEFA production from the three assessed feedstocks (soybean, palm and UCO) were due to several reasons:

- Differences in agricultural processes, something expected since most models have different location of soybean/palm production;
- Substitution procedure in GHGenius in opposition to the allocation methods considered in the other LCA models, which contributes to either considerably

decrease or increase final emissions depending on the feedstock or industrial pathway;

- High use of renewable energy sources in industrial processes considered in the VSB model;
- High variation of energy intensity between models for the industrial pathway;
- Differences in modals and distances of feedstock transportation that are specific for each country.

The location of feedstock production and industrial process are specific for each model and, therefore, variable results are expected in terms of GHG emissions per MJ of biofuel. In general, there are differences in the inputs data and, also, in methodological choices. Some of these differences are justified by the particularities of each model, while others can be harmonized. It is also worth noting that this study has proceeded to consider both HVO and HEFA routes as producing a hydrocarbon mix with similar applications, since the production of either renewable diesel or renewable jet fuel through them are practically identical. It was assumed that the impact of an extra consumption of hydrogen for an isomerization step would be minimal and that the energy-based allocation employed in the HVO-based models BioGrace and New EC would minimize the influence on determining the carbon intensity of biojet fuel when a fractionation of the hydrocarbon mix is carried out.

To harmonize the models, default data and parameters (such as agricultural and industrial inputs, emission factors and allocation procedure) were retrieved from the VSB database and entered on three other models. With this approach, it was possible to identify the main differences and to reach similar impacts from different LCA models considering the same production system, as shown in Figure ES1. Only the soybean FAME pathway was harmonized in this study. It is important to highlight that the New EC was not included in the harmonization procedure: despite the data for several scenarios being available online (and an external user would be able to "rebuild" the calculation structure, if needed), the spreadsheet with the calculation tool is locked for edition by users. This led to the removal of New EC from this specific section of the study since the purpose of a harmonization exercise is not only identifying the differences between assumptions and input data from each model, but also understanding the underlying features of the calculation mechanism itself.

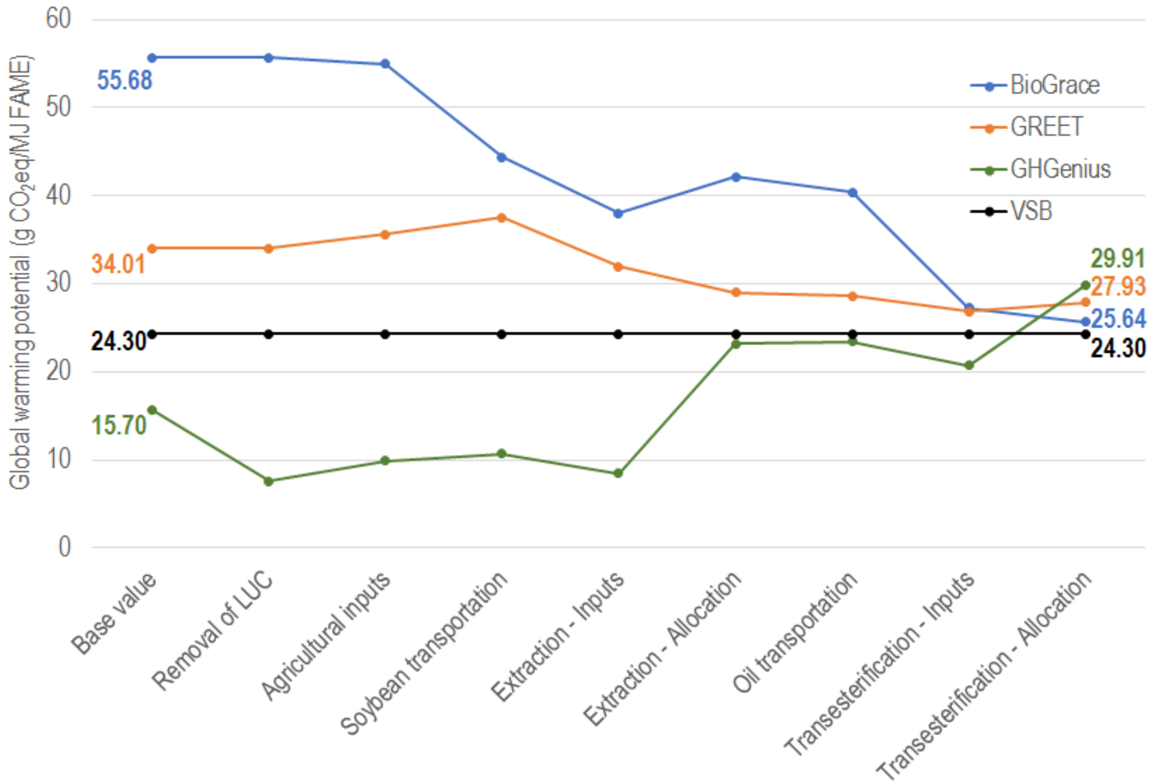

Figure ES1: Harmonization of soybean FAME production in selected LCA models using VSB data and parameters

In this sense, there is room for discussion and standardization of models in order to decrease the variance of input data and approaches (e.g. necessity of a collection and pre-processing phases for UCO) and thus "pre-harmonize" all models. An effort to build a harmonized data set of input data for the technological pathways and to update the databases of the main models would benefit the community and deliver better GHG emission results for the life cycle assessment of biofuels production.

1. Introduction

In the medium term, the reduction in the global dependence on fossil-based fuels passes by the synthesis of biofuels. Bioenergy can provide around 17% of final energy demand and 20% of cumulative carbon savings by 2060 (2°C scenario), to meet these future projections, the biofuel production needs to increase ten-fold and biomass feedstock around five-fold compared to current production; highlighting the importance of wastes and residues that can provide two thirds of feedstock demand (OECD/IEA, 2017). Currently, ethanol and biodiesel are the biofuels with the largest production volumes at 101 billion L and 36 billion L in 2016, respectively (OECD/IEA, 2017), and positive environmental impacts on the displacement of fossil fuels (Cavalett et al., 2012; Collet et al., 2011; Kim and Dale, 2005). More recently, a growing pressure over the substitution of conventional jet fuel by renewable alternatives has been put over both airlines and countries (Klein et al., 2018; O'Connell et al., 2019). According to recent estimates (Kousoulidou and Lonza, 2016), airline operations around the world were responsible for around 2% of total carbon emissions in 2012. The use of sustainable alternative aviation jet fuel, simply designated biojet fuel, in substitution to fossil jet fuel is one of the main moves towards the reduction of impacts derived from global warming. For biojet fuel, specifically, several policies have been put into place worldwide to enforce it use in the coming years, among which the CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) stands out (Larsson et al., 2019). The substitution of fossil fuels by renewable ones, in fact, needs to occur to attend the increasing requirements to reduce greenhouse gases (GHG) emissions and other environmental impacts. Novel advanced biofuels with very low sustainability impacts will be needed to constitute part of the global energy matrix in addition to more established, conventional biofuels. Another fact drawing attention towards alternative sources of carbohydrates and lipids is the concern with land use change combined with food production issues (Doshi et al., 2016).

The medium and long-term benefits of bioenergy depend on the reduction of GHG emissions promoted by the use of biofuels in substitution to their fossil counterparts (IEA, 2017). Sustainability impacts of biofuels, in turn, can be quantitatively determined through a Life Cycle Analysis (LCA) methodology. This method is widely employed for the environmental assessment of products and processes, including bioenergy production. The evaluation considers impacts in the use of resources and emissions typically included in bioenergy systems. It also allows covering substantially broader environmental aspects, ranging from greenhouse gases (GHG) emissions and fossil resource depletion to acidification, toxicity, and land use aspects.

In this way, this report presents the main results of the study carried out as part of Phase 2 of the project entitled "Comparison of Biofuel Life Cycle Assessment Tools", which is included in the activities of Task 39 (Commercializing Liquid Biofuels from Biomass) of the International Energy Agency Bioenergy Technology Collaboration Program (IEA Bioenergy). This document contains a thorough comparison of selected LCA models for the estimation of GHG emissions associated to the production of biofuels from oil crops (soybean and palm) and used cooking oil (UCO): four publicly-available regulatory models (BioGrace/GHGenius/GREET/New EC) and an assessment platform developed by CTBE/CNPEM, in Brazil (Virtual Sugarcane Biorefinery or VSB). Two types of biofuels were considered in this study: conventional biodiesel (also known by the acronym FAME, Fatty Acid Methyl Esters) and renewable jet fuel (known either by the acronyms HVO – Hydrotreated Vegetable Oil or HEFA – Hydroprocessed Esters and Fatty Acids).

Other studies have previously assessed biofuels pathways. A recent report from IEA (IEA, 2018) performed a detailed assessment of the *status quo* of advanced biofuels, main feedstocks and conversion technologies. Two other studies from (S&T²) Consultants Inc. can also be cited. The first one, from 2013, assessed six pathways (petroleum, corn ethanol, sugarcane ethanol, cellulosic ethanol, soybean biodiesel/renewable diesel and natural gas) from four models (BioGrace/EPA RFS2/GHGenius/GREET) to understand the main differences and characteristics of each model ((S&T)² Consultants Inc., 2013). Later, CRC Project E-102-2 ((S&T)² Consultants Inc., 2018) analyzed the source of data used in three models and six pathways (RFS2 was not included).

2. Motivation and objectives

The main motivation of comparing different LCA models lies in the identification of the main differences and commonalities in methodological structures, calculation procedures, and assumptions to demonstrate the possibility of obtaining homogeneous results for similar production chains. In this way, the first part of Phase 2 targets the understanding of the particularities of GHG emissions of FAME and HVO/HEFA production systems from vegetable oils in different parts of the world were considered as feedstock for these production chains: soybean oil, palm oil, and UCO.

One of the main objectives is to identify the main differences and commonalities in methodological structures, calculation procedures, and assumptions, providing a detailed understanding of how models determine GHG emissions. With the presented analysis, it was possible to evaluate all five selected models, comparing the LCA differences from each production system. The main reasons for each identified difference are pinpointed in a case by case basis (for example, higher use of fertilizers, higher transport distances, consumption of energy and inputs in industrial processes, transport efficiencies in all phases of the biofuel production chain and use, among other factors and particularities).

The second part of Phase II will focus on the comparison of LCA models regarding the production of second-generation (2G) ethanol from different lignocellulosic biomasses. This part of the work will be presented in a separate report expected by May/2019.

3. Assessed models

Five LCA models were compared in this study:

- BioGrace (Agentschap NL, now Netherlands Enterprise Agency – The Netherlands) - *Harmonised Calculation of Biofuel Greenhouse Gas Emissions in Europe;*
- GHGenius ((S&T)^2 Consultants Inc. – Canada);
- GREET (Argonne National Laboratory – United States of America) - *The Greenhouse Gases, Regulated Emissions and Energy Use in Transportation Model;*

- New EC (JRC – European Community) - *Biofuels pathways. Input values and GHG emissions. Database;*
- VSB (CTBE/CNPEM – Brazil) - *Virtual Sugarcane Biorefinery*.

The main characteristics of each model are presented in Table 1.

Table 1: Main characteristics of the five assessed models

	BioGrace	**GHGenius**	**GREET**	**New EC**	**VSB**
Model version	4d (2015)	5.0a (2018)	2017	2017	2018
Developed for regulatory use	Yes	No[1]	Yes	Yes	No
IPCC GWP method	2001	1995, 2001, 2007, 2013	2013	2013	2013
Default global warming gases	CO_2, CH_4, N_2O	CO_2, CH_4, N_2O, CO, VOC, NO_x, fluorinated compounds	CO_2, CH_4, N_2O	CO_2, CH_4, N_2O	CO_2, CH_4, N_2O
Lifecycle data	JRC (2008)	Internal	Internal	JRC (2017)	Ecoinvent
Functional unit	MJ	km MJ	km, mile Btu, MJ	MJ	km MJ
Default allocation	Energy	Mostly substitution[2]	Variable[3]	Energy	Economic
Land use change	C stocks	Internal model	CCLUB/GTAP	C stocks	-
Possible boundaries	Well-to-pump	Well-to-wheel	Well-to-wheel	Well-to-pump	Well-to-wheel

[1] GHGenius has not been developed as a regulatory tool, although it is currently being used as one
[2] For soybean meal, mass allocation is also used
[3] For FAME and HVO/HEFA, mainly energy/mass/economic allocations are used, despite the default allocation in GREET being displacement (substitution), especially for electricity

In this study, default values were used in the comparisons. This means that, even if there is the possibility of changing the input values in all models, the study only considers the numbers obtained from the unmodified versions just as any user would if they downloaded the models directly from their host websites.

GHGenius is the only model to include default land management change (LMC) emissions in most biomass production systems. The other four models, except for the VSB, allow the user to model land use changes (LUC) whenever needed, although such emissions are not considered as default inputs in the existing routes. The 2018 version of GREET includes LMC emissions as a default input in some biomass production systems (such as of soybean and palm) (Chen et al., 2018). GREET considers LUC from CCLUB SOC changes and GTAP values for land use changes. In BioGrace and New EC, it is possible to model LUC based on C stocks.

Finally, boundaries must be set so as the LCA analysis is consistent throughout the models. The results presented in this report are limited to cradle-to-gate and cradle-to-pump analyses so as to avoid performing comparison of vehicle fleets with completely different characteristics – those of the United States of America, Canada, Europe, and Brazil. In spite of that, GHGenius, GREET and VSB are models which easily allow users to model vehicle emissions whenever needed; BioGrace and New EC, in the other hand, limit user interaction to agricultural, industrial and logistic inputs.

4. Assessed feedstock-pathway duos

Feedstock/pathway duos were chosen in order to maximize the number of models having a default full pathway for comparison. The following conversion pathways were assessed in this report:

- FAME production from palm oil, soybean oil, and UCO;
- HVO/HEFA production from palm oil, soybean oil, and UCO;

For each feedstock/technology duo, a comparison is carried out considering the results obtained through Life Cycle Analysis (LCA) for the default conditions to which the five models (BioGrace/GHGenius/GREET/New EC/VSB) were developed. For example, in the conversion of soybean to biofuels, the BioGrace model assumes the production of soybean occurring in Brazil, the extraction and the industrial conversion of soybean oil in Europe, as well as biofuel use in Europe. A similar situation occurs when palm is the feedstock of choice: BioGrace/GHGenius/GREET/New EC models consider palm oil production in Asia for all proposed conversion routes. For all other alternatives, the whole production chain (feedstock production, oil extraction, biofuel production, and its use) takes place in the country of origin of each LCA model. In the case of UCO, the collection region and transport conditions vary among each LCA model.

Following, the detailed agricultural production systems and the industrial comparison strategy for the technology/feedstock duos presented above are narrowed.

4.1. Description of agricultural production systems

4.1.1. Soybean

Based on Silva et al. (2010), Figure 1 presents the simplified flowchart of the production process of soybean. With season period ranging between 100 and 160 days, soybean planting happens from October to December and it is harvested between January and May in Brazil. After harvesting, soybean grains are normally dried to 15% moisture and kept in regional storehouses. It can be sold in the international market or processed to produce oil and soybean meal, typically used for animal feed. The oil extraction plant is considered to be located near to the production site, and transportation distances are variable according to the extraction plant capacity.

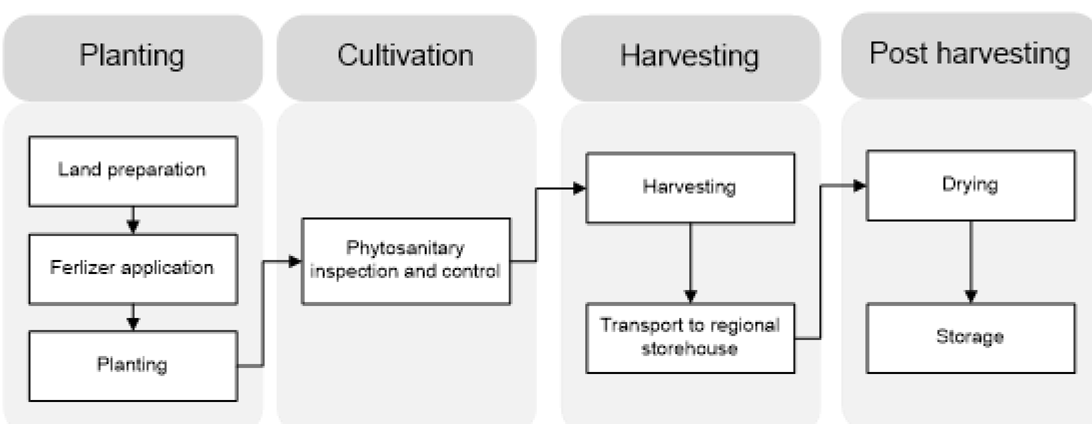

Figure 1: Simplified flowchart of soybean production

Particularities of each LCA model

BioGrace: considers production in Brazil.

GHGenius: considers mass allocation for soybean oil extraction as default for soybean production. Although production of soybean in Ontario would be more representative, the default pathway in GHGenius considers soybean production in Central Canada. Besides, it is the only model to consider LMC emissions as a default input and it allows modelling of LUC.

GREET: considers production in USA.

New EC: considers a weighted average production in Argentina, Brazil, USA and EU.

VSB: considers production in Brazil.

Table 2 presents the agricultural inputs for soybean production for the five assessed models.

Table 2: Agricultural inputs per tonne of soybean, dry basis (unallocated)

	BioGrace	GHGenius	GREET	New EC	VSB	Unit
Soybean productivity (moist basis)	2,798	2,980	-	2,788	3,240	kg/ha.yr
Total energy						
Energy input	883	481	822	724	391	MJ
Diesel	24.6	8.4	16.2	20.2	10.7	L
Natural gas	-	-	1,134.7	-	-	L
Electricity	-	11.6	11.0	-	-	kWh
Gasoline	-	2.5	4.0	-	-	L
LPG	-	1.1	1.4	-	-	
Inputs						
N	3.4	1.7	2.0	1.9	2.4	kg N
K_2O	26.1	10.1	12.6	15.8	31.6	kg K_2O
P_2O_5	27.8	5.9	7.9	16.4	25.9	kg P_2O_5
Soil correctives[1]	-	1.0	-	170.6	230.0	kg inputs
Pesticides/herbicides	1.1	0.5	0.8	1.3	0.8	kg inputs
Seeds[2]	-	41.7	-	-	-	kg
Field emissions[3]						
N_2O	0.9	0.9	0.8	1.0	0.7	kg N_2O
CO_2	-	-	-	71.8	79.9	kg CO_2
LMC	-	292.4	-	-	-	kg CO_2eq

[1] $CaCO_3$, $CaSO_4$ and sulphur

[2] Only GHGenius considers seeds as an input (low emission factor)

[3] Emissions from agricultural residues, from limestone and N fertilizer, and N fixation

4.1.2. Palm

Palm is a perennial crop, and the production of palm fruits starts three years after planting and gradually increases until the 7th year, and remains relatively stable until the 18th year, when it starts to decrease. During the period of greatest productivity, 25 to 30 tonnes on average of fresh fruit bunches (FFB) can be achieved per hectare in Brazil. About 25 years after planting, system operation is no longer economically feasible due to reduced productivities and increased cost of harvesting resulting from the plant height. Figure 2 presents the simplified flowchart of palm production based on Macêdo et al. (2010). During the productive period, production is performed throughout the year. Due to the rapid acidification of the fruit, it is necessary to process it just after harvesting (not exceeding 72 hours), making it necessary to install the oil extraction plant next to the crop site.

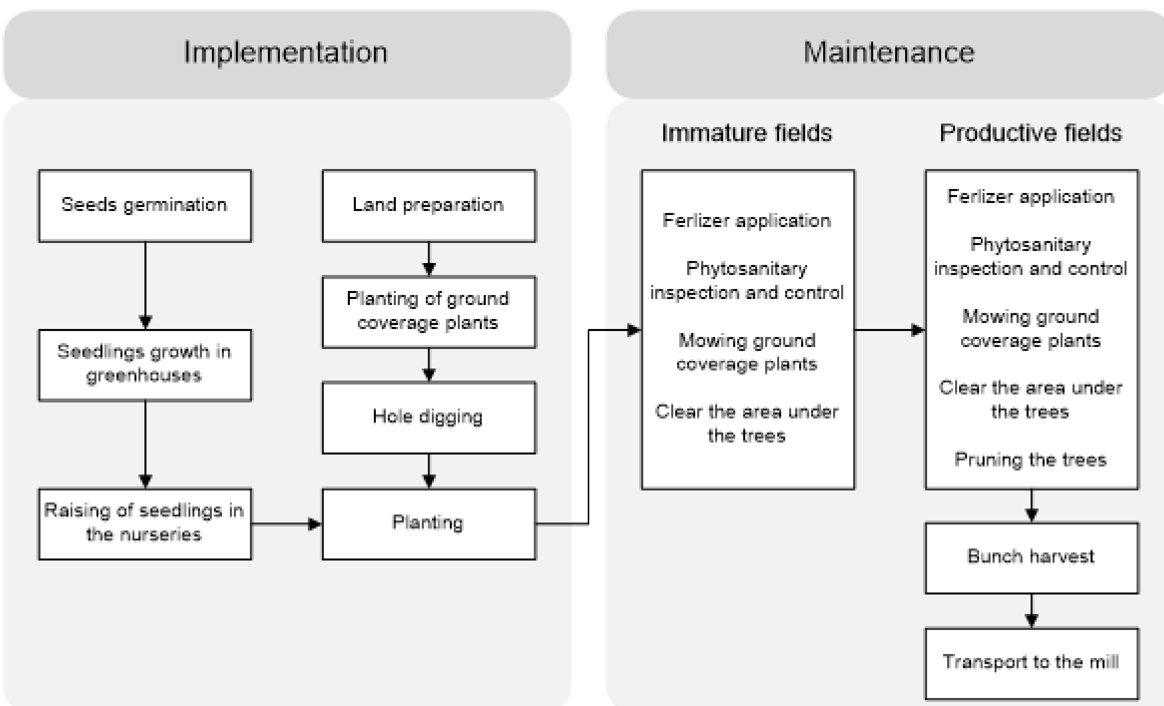

Figure 2: Simplified flowchart of palm production

Particularities of each LCA model

BioGrace: considers production in Asia using mainly diesel in agricultural steps.

GHGenius: considers production in Asia and LMC emissions as a default input.

GREET: considers production in Asia.

New EC: considers production in Asia (Malaysia and Indonesia).

VSB: considers production in Brazil.

In Table 3 the agricultural inputs for palm production are presented, considering the five assessed models.

Table 3: Agricultural inputs per tonne of palm, dry basis (unallocated)

	BioGrace	GHGenius	GREET	New EC	VSB	Unit
Palm productivity (moist basis)	19,000	19,941	-	19,000	16,615	kg/ha.yr
Energy						
Energy input	165	138	219	155	158	MJ
Diesel	4.6	3.6	6.7	3.6	3.7	L
Inputs						
N	10.2	4.6	10.5	7.7	7.9	kg N
K_2O	15.9	11.7	-	13.9	7.9	kg K_2O
P_2O_5	11.5	3.1	-	2.5	7.9	kg P_2O_5
Soil correctives[1]	-	3.1	-	-	10.8	kg inputs
Pesticides	0.7	0.2	-	1.1	-	kg inputs
EFB compost	46.7	-	-	340.9	-	kg
Field emissions[2]						
N_2O	0.3	0.4	0.2	0.7	0.24	kg N_2O
CO_2	-	-	-	37.3	17.12	kg CO_2
LMC	-	321.0	-	-	-	kg CO_2 eq

[1] $CaCO_3$ and sulphur

[2] Emissions from agricultural residues, from limestone and N fertilizer

4.1.3. Used Cooking Oil (UCO)

UCO refers to oils and fats, which have been previously used for cooking or frying in both industrial and domestic applications. This feedstock has gained increased attention over the last years due to its low price in comparison to unused vegetable oils and the low (or null, even, depending on the approach) associated environmental burden, which make it a favorable option for the production of liquid biofuels with sustainable attributes.

Particularities of each LCA model

BioGrace: considers UCO (waste oil) entering the industrial site with null associated GHG emissions (residue with zero emissions for collection and transportation).

GHGenius: considers UCO as "waste grease" before pre-processing step and "yellow grease" after pre-processing step

GREET: does not present any conversion pathways for UCO nor its collection as default options; therefore, the model was not included in the analyses carried out for this feedstock.

New EC: considers 20% of UCO coming from overseas (transport distance of over 7,000 km), with the remainder coming from nearby locations (transport distance of 100 km).

VSB: considers no refining processes for UCO before transesterification/hydrogenation.

4.2. Description of industrial production systems

4.2.1. Fatty Acid Methyl Esters (FAME)

The production of FAME, also commonly known as biodiesel, is an established industrial conversion of vegetable oils, animal fat, and UCO into a liquid biofuel (IEA, 2018). The pathway consists in converting triglycerides into esters of fatty acids through transesterification with alcohols (usually methanol), producing also glycerin as a byproduct, as schematically shown in Figure 3. All five models in this study consider methanol as the alcohol of choice for the transesterification reaction. Currently, around 66 countries worldwide have different mandates of biodiesel blend with conventional (fossil) diesel (Biofuels Digest, 2018).

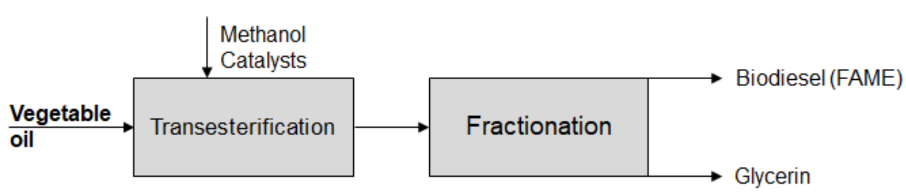

Figure 3: Main steps of vegetable oil processing into FAME

Particularities of each LCA model

BioGrace: employs a mix of sodium hydroxide (NaOH) and carbonate (Na_2CO_3) as catalysts for the transesterification reaction; considers a step of refining prior to transesterification.

GHGenius: considers the highest input of n-hexane in the transesterification process and it is the only model to consider citric acid (small amount) as input for transesterification. The co-product credits for glycerin are high.

GREET: considers sodium hydroxide (NaOH) as the catalyst for the transesterification reaction; apart from glycerin, a second coproduct is obtained during the industrial conversion as default: free fatty acids (heavy distillation bottoms).

New EC: considers a preliminary step of oil refining prior to transesterification; employs mainly sodium methylate as catalyst for transesterification. When UCO is used as feedstock, the transesterification is carried out mainly with potassium hydroxide (KOH) as catalyst.

VSB: considers that FAME in Brazil is produced with considerable inputs of renewable energy to the system – mainly eucalyptus for generation of the required thermal energy.

4.2.2. Hydrotreated Vegetable Oil (HVO)/Hydroprocessed Esters and Fatty Acid (HEFA)

The HEFA route, previously known as HVO, converts vegetable oils with hydrogen (H_2) over catalytic beds to convert triglycerides into hydrocarbons. HVO/HEFA routes can process several types of vegetable oils with distinct qualities (fatty acid profile, acid value, degree of unsaturation, among others) (IEA, 2018). The produced fuel cuts are composed of drop-in molecules, which allow their blend with conventional (fossil) fuels without incurring in changes or additional investments to adapt piping and engines. Despite the wide interest on such pathways for the production of advanced biofuels with low GHG emissions, their deployment in large-scale facilities is still limited although steadily gaining importance worldwide (Mawhood et al., 2016).

Most HVO/HEFA routes are composed of the general steps shown in Figure 4 or by a slight variation thereof. Vegetable oil enters a catalytic hydrotreatment reactor along with H_2 for sequential decarboxylation, decarbonylation, and hydrogenation of triglycerides for the removal of structural oxygen and carbon-carbon double bonds. Next, a similar reactor catalytically hydrogenates the reactional mixture from the first reactor in order to produce isomers and cracks long carbon chains into paraffinic, fuel-range molecules. The reactors have different dimensions and catalyst loadings. The final step involves fractionation of the products in two separate columns: one separating off-gas from water and a second one distilling hydrocarbon fuels (naphtha, paraffinic biojet fuel and diesel). The remainder of the products are composed of off-gas and water generated during the reactions.

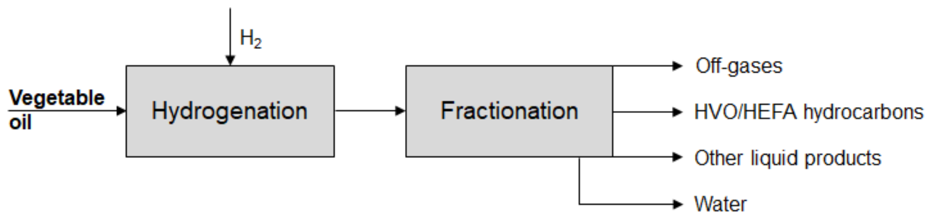

Figure 4: Main steps of vegetable oil processing into HVO/HEFA

Nearly every biojet fuel production technology requires H_2 as a process input. This H_2 must be produced in a dedicated unit through several possible techniques: biomass or fossil feedstock gasification, natural gas steam reforming, off-gas steam reforming, ethanol reforming (either electrochemically- or steam-assisted), and water electrolysis, for instance. The degree of unsaturation of fatty acids constituting the triglycerides directly influences the amount of needed H_2 for the conversion of vegetable oils into liquid hydrocarbons.

Particularities of each LCA model

BioGrace: considers the purchase of H_2 for the hydrogenation reaction; electricity is generated on-site through the combustion of light gases obtained in the hydrogenation process, with the surplus being exported to the grid; the model has no default HVO/HEFA pathway from soybean, although this specifically route can be built from the default assumptions of soybean production and HVO/HEFA conversion of palm oil.

GHGenius: has the highest inputs of energy (mostly electricity and natural gas) among the models; besides hydrotreated renewable jet (HRJ), GHGenius has default pathways for hydrotreated renewable diesel (HRD) and hydrotreated renewable gasoline (HRG).

GREET: despite the choice for assessing the production of renewable jet fuel-like molecules in this study, the GREET model also presents multiple default pathways for the production of renewable diesel as the main fuel.

New EC: considers data from the NExBTL process, including on-site H_2 generation, for the production of a BTL-like fuel.

VSB: considers the production of HEFA in Brazil to be carried out with considerable inputs of renewable energy to the system – mainly eucalyptus, for generation of the required thermal energy.

This study has proceeded to consider both HVO and HEFA routes as producing a hydrocarbon mix with similar applications, since the production of either renewable diesel or renewable jet fuel through them are practically identical. It was assumed that the impact of an extra consumption of hydrogen for an isomerization step would be minimal and that the energy-based allocation employed in the HVO-based models BioGrace and "New EC" would minimize the influence on determining the carbon intensity of biojet fuel when a fractionation of the final hydrocarbon mix is carried out.

4.3. Emission factors

The related

Table *4* and Table 5 contain the retrieved emission factors for the default inputs of both agricultural and industrial steps in the five models of the study. Despite the models having emission factors associated to several other compounds, these are not presented in the cited tables since they are not employed as default inputs in the analyzed pathways.

Table 4: Emissions factors for the agricultural phase

	BioGrace	GHGenius	GREET	New EC	VSB	Unit
Diesel	88	111	95	95	84	g CO_2eq/MJ
Natural gas	68	-	78	66	-	g CO_2eq/MJ
Electricity	129	61	188	141	40	g CO_2eq/MJ
Gasoline	-	103	80	-	-	g CO_2eq/MJ
LPG	-	71	88	-	-	g CO_2eq/MJ
N	5,881	3,104	4,548	4,572	2,799	g CO_2eq/kg
K_2O	576	426	686	417	545	g CO_2eq/kg
P_2O_5	1,011	2,016	1,807	542	1,468	g CO_2eq/kg
CaO	130	-	-	70	-	g CO_2eq/kg
$CaCO_3$	-	-	-	-	13	g CO_2eq/kg
Gypsum	-	-	-	-	2	g CO_2eq/kg
Sulphur	-	113	-	-	-	g CO_2eq/kg
Pesticides	10,971	21,791	24,733	12,011	10,076	g CO_2eq/kg
Herbicides	-	-	21,854	-	10,448	g CO_2eq/kg

Table 5: Emissions factors for the industrial phase

	BioGrace	GHGenius	GREET	New EC	VSB	Unit
n-Hexane	81	78	87	80	-	g CO_2eq/MJ
Coal	-	-	101	-	-	g CO_2eq/MJ
Residual oil	-	-	96	-	-	g CO_2eq/MJ
Forest resources	-	-	3	-	2	g CO_2eq/MJ
Natural Gas	-	60	70	-	-	g CO_2eq/MJ
Diesel	-	-	95	-	-	g CO_2eq/MJ
Renewable natural gas	-	-	24	-	-	g CO_2eq/MJ
Fuller's Earth	200	-	-	-	-	g CO_2eq/kg
H_3PO_4	3,012	1,543	853	3,125	1,676	g CO_2eq/kg
HCl	751	756	1,980	1,061	1,836	g CO_2eq/kg
Na_2CO_3	1,190	-	-	-	-	g CO_2eq/kg
NaOH	469	888	2208	530	1513	g CO_2eq/kg
Citric acid	-	1,476	-	-	-	g CO_2eq/kg
Nitrogen	-	132	-	-	-	g CO_2eq/kg
Sodium methylate	-	1,981	-	2,426	1,836	g CO_2eq/kg
Methanol	100	22	30	97	28	g CO_2eq/MJ
Hydrogen	88	-	87	-	20	g CO_2eq/MJ

In the Results section, the GHG emissions values of the New EC model values correspond to those calculated using the inputs available from the 2017 JRC database (agricultural and industrial inputs, transportation distances and efficiencies, and emission factors) and the calculation structure of BioGrace. With this procedure, slightly different results from the default values presented in the New EC model were reached. The remaining differences may be consequence of minor points between both models. This is clearly indicated whenever necessary and the default values in New EC are also shown for discussion purposes.

5. Soybean biofuels

The main objective of this section is to present a comparison between pre-existing scenarios of soybean biofuels production (FAME and HVO/HEFA) in the LCA models and identification of the particularities leading to different outcomes in the analyses.

5.1. FAME

In the case of FAME from soybean, the production location of the feedstock and the FAME producing units varies among the five models assessed (

Figure 5).

Figure 5 also presents the boundaries of soybean FAME production for each model assessed. The cradle-to-gate approach considers the emissions of FAME production up to the gate of the producing unit, while the cradle-to-pump analysis includes additional impacts of biofuel distribution to fuel pumps.

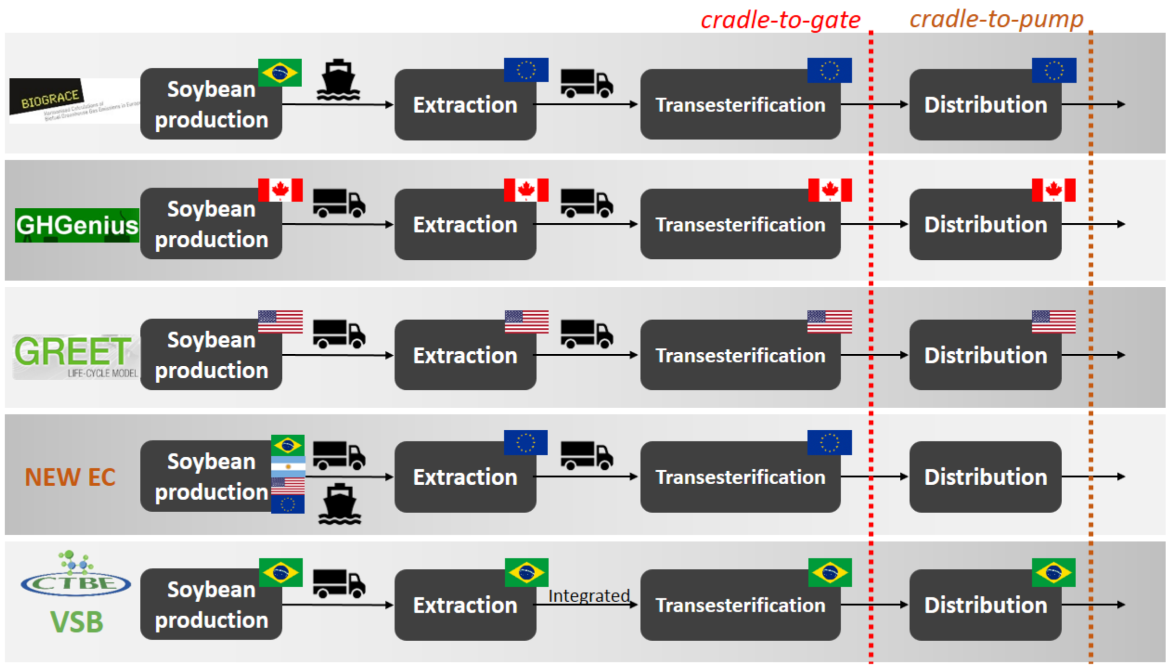

Figure 5: System boundaries - FAME from soybean

A clear difference between the origin of soybean among both European models has been identified: while BioGrace considers soybean as coming 100% from Brazil, the New EC model considers a mix of EU production and imports from other countries (Brazil, Argentina, and USA). In this analysis, this mix of soybean production from the New EC input data when inserting them in the BioGrace model was considered.

All models consider soybean meal as a co-product from the extraction of oil from soybean, and glycerin from the transesterification step. The GREET model, on the other hand, also considers glycerin and a heavy distillate (FFA) fraction as coproducts of FAME production from soybean oil. This is probably a mistake in the default process "Vegetable oil transesterification (Biodiesel)".

The industrial inputs vary significantly among the models, as summarized in Table 6 and Table 7. Only BioGrace and New EC consider a refining step before transesterification. In addition, the New EC model considers two drying steps for conditioning of soybean before the industrial phase (one prior to soybean transportation and one prior to oil extraction), consuming around 9.3 10^{-3} MJ/MJ oil, mainly in the form of light petroleum gas (LPG), natural gas, heating oil, diesel, and electricity. Internal calculations were done with LHV values, except for GHGenius (calculations and process inputs consider HHV values). All final emissions are given in MJ of biofuels (LHV basis).

Table 6: Industrial inputs per MJ of soybean oil

	BioGrace	GHGenius	GREET	New EC	VSB	Unit
Soybean oil extraction						
Electricity	48.08	24.97	23.25	16.23	19.04	10^{-3} MJ
Natural gas	226.07	140.89	107.78	90.96	-	10^{-3} MJ
n-Hexane	6.42	21.25	3.07	3.66	7.59	10^{-3} MJ
Coal	-	-	53.05	-	-	10^{-3} MJ
Residual oil	-	-	1.67	-	-	10^{-3} MJ
Diesel	-	-	0.83	-	0.63	10^{-3} MJ
Forest resources	-	-	1.67	-	154.66	10^{-3} MJ
Renewable natural gas	-	-	0.83	-	-	10^{-3} MJ
Soybean oil refining						
Electricity	1.07	-	-	2.42	-	10^{-3} MJ
Natural gas	12.80	-	-	6.47	-	10^{-3} MJ
Fuller's earth	0.23	-	-	-	-	g
NaOH	-	-	-	0.07	-	g
H_3PO_4	-	-	-	0.01	-	g

From Table 6, it can be seen that GREET is the only model to consider coal and residual oil as inputs for soybean oil extraction; New EC is the only model to consider NaOH and H_3PO_4 as inputs for the refining process; and VSB is the only model to not use natural gas for soybean oil extraction (energy production is mainly fueled by forest resources, namely eucalyptus chips).

Table 7 clearly indicates that the BioGrace model considers a significantly higher input of methanol for transesterification than the remaining models; GHGenius is the only model to consider citric acid and coal for the transesterification process, however in considerably low amounts; and New EC is the only model to not consider H_3PO_4 in the transesterification process.

Table 7: Industrial inputs per MJ of soybean FAME

	BioGrace	GHGenius	GREET	New EC	VSB	Unit
Soybean oil transesterification						
Electricity	6.07	3.25	3.90	4.71	4.16	10^{-3} MJ
Natural gas	111.76	21.60	31.39	36.70	-	10^{-3} MJ
Coal	-	0.01	-	-	-	t
Diesel	-	-	0.63	-	0.01	10^{-3} MJ
Forest resources	-	-	1.67	-	35.03	10^{-3} MJ
H_3PO_4	0.06	0.02	0.01	-	0.01	g
HCl	0.75	0.33	0.07	0.10	0.37	g
Na_2CO_3	0.09	-	-	-	-	g
NaOH	0.25	0.01	0.01	-	0.04	g
Citric Acid	-	0.02	-	-	-	g
Nitrogen	-	0.70	0.06	-	-	g
Sodium methylate	-	0.18	-	0.11	0.62	g
Methanol	81.84	51.80	58.09	51.10	58.04	10^{-3} MJ

As previously mentioned, the locations of soybean and FAME production vary among the models. In this way, the transportation distances and modals are particular to each of the models (Table 8). BioGrace, for instance, considers ocean transportation of soybean from Brazil to Europe, while the default pathway in GHGenius presents short transportation distances of soybean and soybean oil compared to the other models. Finally, the VSB model considers soybean oil extraction and transesterification as being located in the same processing unit. Modal shares in GREET and New EC are indicated in parentheses in Table 8 and Table 9.

Table 8: Transportation of soybean (grains and oil) parameters

	BioGrace	GHGenius	GREET	New EC	VSB	Unit
Soybean transportation						
Truck	700	100	16 (MHD)	517	324	km
Truck	-	-	64 (HHD)	-	-	km
Train	-	-	-	179	-	km
Inland ship	-	-	-	614	-	km
Ocean	10,186	-	-	9,381	-	km
Soybean oil transportation						
Barge	-	-	837 (40%)	-	-	km
Train	-	-	1,126 (20%)	-	-	km
Truck	-	50	129 (HHD) (40%)	-	116	km

MHD: medium-heavy-duty truck
HHD: heavy-heavy-duty truck

When considering cradle-to-pump boundaries, additional inputs for FAME distribution are taken into account (Table 9). BioGrace and New EC also consider electricity consumption in depots in this step; GREET and New EC consider FAME distribution shared in different transportation modals (Table 9); finally, distribution in pipelines is only considered in GREET. BioGrace, GREET and New EC consider an intermediate terminal before final FAME distribution by truck.

Table 9: Soybean FAME distribution

	BioGrace	GHGenius	GREET	New EC	VSB	Unit
Electricity	4.24	-	-	4.24	-	10^{-3} MJ
Truck	150	183	-	305 (11%)	300	km
Ocean	-	-	-	1,118 (27%)	-	km
Barge	-	-	322 (49%)	153 (44%)	-	km
Train	-	997	789 (5%)	381 (4%)	-	km
Pipeline	-	-	177 (46%)	- (14%)	-	km
Truck (final distribution)	150	-	48	150	-	km

HD: heavy-duty truck

5.2. HVO/HEFA

As in the case of FAME, the production of soybean and HVO/HEFA varies among the models assessed (Figure 6). System boundaries for soybean HVO/HEFA are the same as presented for soybean FAME (Figure 5).

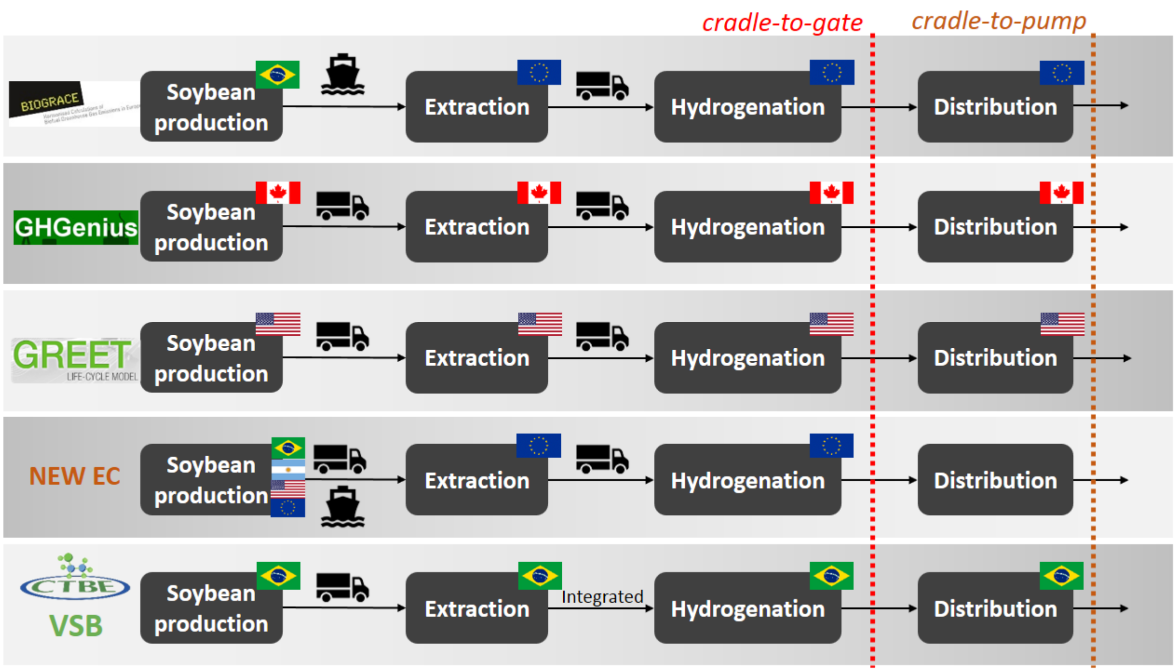

Figure 6: System boundaries - HVO/HEFA from soybean

It is worthwhile mentioning that BioGrace has no pathway for soybean HVO/HEFA production and it was created considering soybean production and extraction inputs from FAME production and hydrogenation inputs from palm oil.

Differently from FAME, the co-products from HVO/HEFA production processes are significantly different among models. Table 10 shows the main co-products considered in each model (the GHGenius model does not specify the nature of "Other gaseous" and "Other liquids" co-products).

Table 10: Products and co-products from soybean HVO/HEFA

	BioGrace	GHGenius	GREET	New EC	VSB
Main product	HVO	Hydrotreated Renewable Jet Fuel (HRJ)	Renewable Jet Fuel	HVO (diesel-like molecule)	Biojet Fuel
Co-products	Natural gas; Electricity	"Other gaseous"; "Other liquids"	Propane fuel mix; Naphtha	Gasoline	Renewable gasoline; Renewable diesel; Electricity

Before hydrogenation, soybean oil is extracted (and refined in BioGrace and New EC models). The input values for oil extraction and refining were presented in Table 6 (please refer to section "Soybean biofuels: FAME"). The hydrogenation inputs vary considerably among the models (Table 11) and only BioGrace and New EC consider a refining step before hydrogenation. Internal calculations were done with LHV values, except for GHGenius (calculations and process inputs consider HHV values). All final emissions are given in MJ of biofuels (LHV basis).

Table 11: Industrial inputs per MJ of soybean HVO/HEFA

	BioGrace	GHGenius	GREET	New EC	VSB	Unit
Soybean oil hydrogenation						
Electricity	-2.33	6.06	4.98	1.55	-	10^{-3} MJ
Natural gas	-12.37	254.66	178.51	109.81	-	10^{-3} MJ
Diesel	-	0.02	-	-	0.01	10^{-3} MJ
Forest resources	-	-	-	-	37.55	10^{-3} MJ
H_3PO_4	-	0.02	-	0.02	-	g
NaOH	-	0.03	-	0.03	-	g
Nitrogen	-	-	-	0.01	-	g
Hydrogen	119.95	172.63	148.32	-	239.99	10^{-3} MJ

In this case, BioGrace carries out a substitution-like procedure in the hydrogenation step of soybean oil. Considering this, electricity and natural gas are produced as co-products and are presented as "negative" inputs; GHGenius has the highest natural gas consumption among the models; New EC has no external H_2 inputs because this model considers the NExBTL process, including on-site H_2 generation, for the production of a BTL-like fuel (the model is also the only to consider nitrogen inputs, however in a very low amount); finally, the VSB model considers no inputs of electricity, since it is generated as co-product, and H_2 consumption is the highest among the studied models. Parameters for soybean and soybean oil transportation were already presented in Table *8* (please refer to section "Biofuels from soybean: FAME").

Considering cradle-to-pump boundaries, Table 12 presents the distribution distances and modal shares among the five assessed models. Again, GREET and New EC splits the distribution of the biofuel among different transportation modals. As for FAME distribution, BioGrace and New EC also consider electricity consumption in depots during the distribution process and only the New EC model considers HVO/HEFA distribution overseas. BioGrace, GREET and New EC consider an intermediate terminal before final FAME distribution by truck. Table 12 presents modal shares in GREET and New EC inside parentheses.

Table 12: Soybean HVO/HEFA distribution

	BioGrace	**GHGenius**	**GREET**	**New EC**	**VSB**	**Unit**
Electricity	4.24	-	-	4.24	-	10^{-3} MJ
Truck	150	225	80 (63%)	305 (11%)	300	km
Ocean	-	-	-	1,118 (27%)	-	km
Barge	-	-	837 (8%)	153 (44%)	-	km
Train	-	644	1,288 (29%)	381 (4%)	-	km
Truck (final distribution)	150	-	48	150	-	km

6. Palm biofuels

The main objective of this section is to present a comparison between pre-existing scenarios of palm biofuels production (FAME and HVO/HEFA) in the LCA models and identification of the particularities leading to different outcomes.

6.1. FAME

Except for VSB and GHGenius, the other models consider palm production and oil extraction in Asia (Indonesia and Malaysia). The VSB models palm production in Brazil and GHGenius in India (Figure 7). Only in VSB the whole biofuel life cycle is located in the same country: Brazil. Figure 7 also presents the boundaries of palm FAME production for each assessed model. Cradle-to-gate boundaries consider emissions of FAME production up to the gate of the producing unit, while a cradle-to-pump approach includes additional impact of the biofuel distribution to fuel pumps.

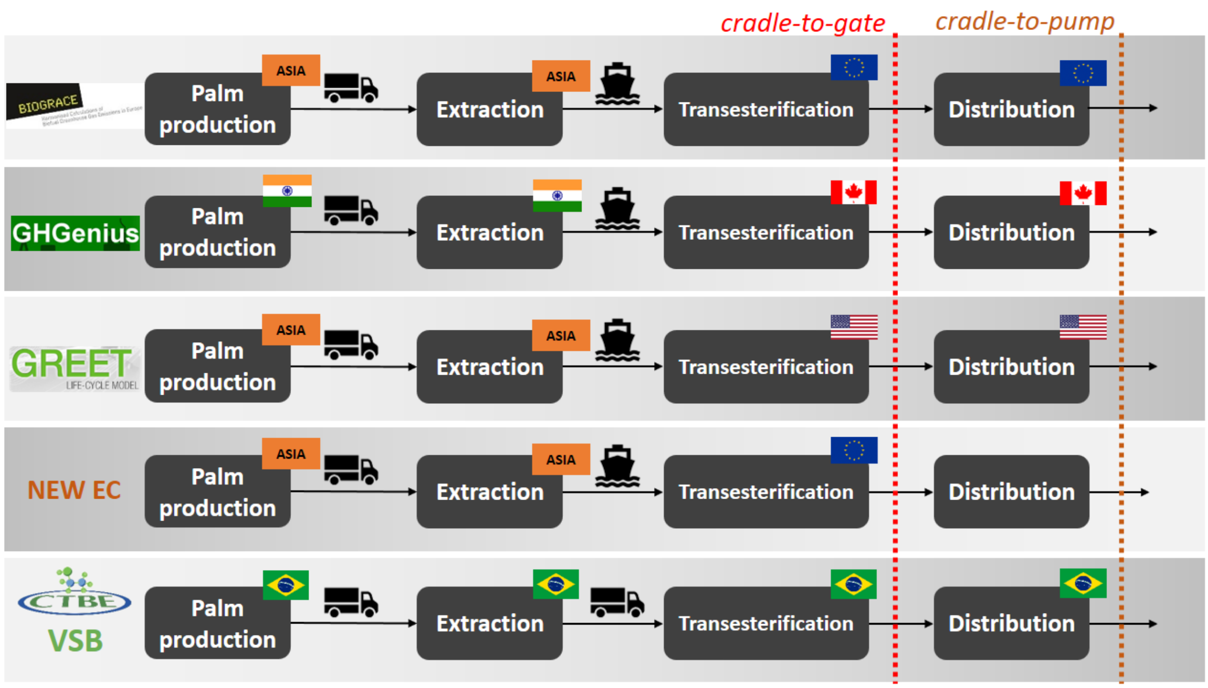

Figure 7: System boundaries - FAME from palm oil

In GREET, the FAME process from palm oil was created considering the default palm production and oil extraction pathway combined with the transesterification inputs from soybean FAME production.

BioGrace, GHGenius and GREET consider palm kernel meal as co-production from palm oil extraction; New EC considers palm kernel meal and palm kernel oil as co-products from palm oil extraction; the VSB model considers palm kernel meal, palm kernel oil and electricity as co-products from extraction processes. All five models consider glycerin as co-product from transesterification of palm oil and GREET also considers a fraction of heavy distillates (FFA).

The industrial inputs vary significantly among the models (Table 13 and Table 14). Only BioGrace and New EC have a predefined option to select the capture or not of CH_4 from oil milling and to include the emissions from palm oil mill effluent (POME) in the process. Furthermore, only these two models consider oil refining before the transesterification step.

Internal calculations were done with LHV values, except for GHGenius (calculations and process inputs consider HHV values). All final emissions are given in MJ of biofuels (LHV basis).

Table 13: Industrial inputs per MJ of palm oil

	BioGrace	GHGenius	GREET	New EC	VSB	Unit
Palm oil extraction						
Electricity	-	-	2.05	0.08	-	10^{-3} MJ
Diesel	-	4.03	11.73	4.45	-	10^{-3} MJ
Forest resources	-	4.39	-	-	952,67	10^{-3} MJ
POME CH_4 emissions	0.944	-	-	0.984	-	g
Palm oil refining						
Electricity	1.07	-	-	1.06	-	10^{-3} MJ
Natural gas	12.79	-	-	3.14	-	10^{-3} MJ
Heating oil	-	-	-	3.87	-	10^{-3} MJ
Fuller's earth	0.23	-	-	0.07	-	g
NaOH	-	-	-	0.06	-	g
H_3PO_4	-	-	-	0.03	-	g

New EC is the only model to consider NaOH and H_3PO_4 in the refining process. The VSB model produces electricity as a co-product from the burning of forest resources, which are used in high amounts in the generation of thermal energy.

Table 14: Industrial inputs per MJ of palm FAME

	BioGrace	GHGenius	GREET	New EC	VSB	Unit
Palm oil transesterification						
Electricity	6.08	3.25	3.90	4.71	4.16	10^{-3} MJ
Natural gas	111.76	42.42	31.39	36.70	-	10^{-3} MJ
Coal	-	0.01	-	-	-	t/MJ
Diesel	-	0.01	0.63	-	0.01	10^{-3} MJ
Forest resources	-	-	-	-	35.03	10^{-3} MJ
H_3PO_4	0.06	0.02	0.01	-	0.01	g
HCl	0.75	0.33	0.07	0.10	0.37	g
Na_2CO_3	0.09	-	-	-	-	g
NaOH	0.25	0.01	0.01	-	0.04	g
Citric acid	-	0.02	-	-	-	g
Nitrogen	-	0.70	0.06	-	-	g
Sodium methylate	-	0.18	-	0.37	0.62	g
Methanol	81.84	51.80	58.09	51.10	58.04	10^{-3} MJ

The natural gas input in BioGrace is considerably higher than in the other models. This model is also the only one to consider a low input of Na_2CO_3 in the transesterification step. GHGenius is the only model to consider coal and citric acid as default inputs, although in low amounts. New EC does not include H_3PO_4 in the transesterification process. Finally, in the VSB model, the consumption of fossil energy resources in the industrial unit is mainly displaced by eucalyptus chips (forest resources).

Regarding palm oil transportation, except for the VSB, all models consider overseas transportation from Asia to each respective location of FAME production (Table 15). However, in the VSB model, since palm is produced in the Northern region of Brazil (state of Pará), relatively far from the biodiesel plant units, the feedstock is transported by truck for long distances. Table 15 and Table 16 present modal shares in GREET and New EC in parentheses.

Table 15: Transportation of palm (FFB and oil)

	BioGrace	GHGenius	GREET	New EC	VSB	Unit
Palm FFB transportation						
Truck	20	20	16, MHD	50	-	km
Palm oil transportation						
Truck	150	-	101, HHD	120	2,000	km
Tanker/Ocean	10,186	12,000	18,910	16,287	-	km
Train/Rail	-	-	805 (50%)	-	-	km
Truck	-	50	161, HHD (50%)	-	-	km

HHD: heavy heavy-duty truck
MHD: medium heavy-duty truck

In the case of cradle-to-pump approach, additional inputs for FAME distribution are considered (Table 16). The split of transportation modals in GREET and New EC for FAME distribution are also presented in Table 16. BioGrace, GREET and New EC consider an intermediate terminal before final FAME distribution by truck.

Table 16: Palm FAME distribution

	BioGrace	GHGenius	GREET	New EC	VSB	Unit
Electricity	4.24	-	-	4.24	-	10^{-3} MJ
Truck	150	225	-	305 (13%)	300	km
Ocean	-	-	-	1,118 (32%)	-	km
Barge	-	-	322 (49%)	153 (51%)	-	km
Train	-	644	789 (5%)	381 (4%)	-	km
Pipe	-	-	177 (46%)	-	-	km
Truck (final distribution)	150	-	48	150	-	km

BioGrace and New EC consider electricity consumption in the distribution step; the GREET model is the only one to consider pipeline as a transportation modal; and New EC is the only model to include the distribution of FAME overseas.

6.2. HVO/HEFA

As in the case of FAME, the production of palm HVO/HEFA varies among the assessed models (Figure 8). System boundaries for palm HVO/HEFA are the same as presented for palm FAME (Figure 7).

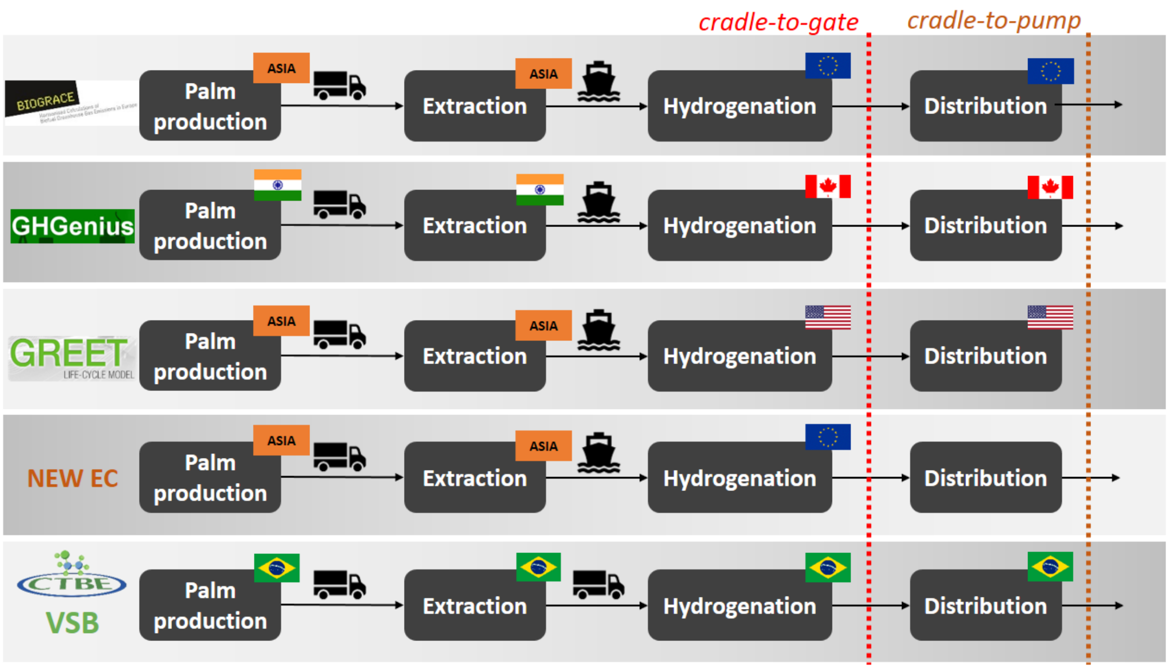

Figure 8: System boundaries - HVO/HEFA from palm oil

BioGrace, GHGenius and GREET consider palm kernel meal as co-product from palm oil extraction. New EC considers palm kernel meal and palm kernel oil as co-products from palm oil extraction, and VSB considers palm kernel meal, palm kernel oil and electricity as co-products from extraction processes.

Differently from FAME, the co-products from palm HVO/HEFA production processes are significantly different among models. Table 17 shows the co-products considered in each model. It is worthwhile noting that GHGenius does not specify the nature of co-products named “Other gaseous” and “Other liquids”.

Table 17: Products and co-products from palm HVO/HEFA

	BioGrace	GREET	GHGenius	New EC	VSB
Main product	HVO	Renewable Jet Fuel	Hydrotreated Renewable Jet Fuel (HRJ)	HVO (diesel-like molecule)	Biojet Fuel
Co-products	Natural gas; Electricity	Propane fuel mix; NG-based FT Naphtha	"Other gaseous"; "Other liquids"	Gasoline	Renewable gasoline; Renewable diesel; Electricity

Inputs for palm oil extraction and refining (only included in BioGrace and New EC models) are presented in Table 13 (for this, please refer to section "Palm biofuels: FAME").

Table 18 shows the variability of default input data among models regarding hydrogenation of palm oil. Internal calculations were done with LHV values, except for GHGenius (calculations and process inputs consider HHV values). All final emissions are given in MJ of biofuels (LHV basis).

Table 18: Industrial inputs per MJ of palm HVO/HEFA

	BioGrace	GHGenius	GREET	New EC	VSB	Unit
Palm oil hydrogenation						
Electricity	-2.33	6.06	4.98	0.86	-	10^{-3} MJ
Natural gas	-12.37	254.66	178.51	85.76	-	10^{-3} MJ
Diesel	-	-	-	-	0.03	10^{-3} MJ
Forest resources	-	-	-	-	53.50	10^{-3} MJ
H_3PO_4	-	0.02	-	0.02	-	g
NaOH	-	0.03	-	0.03	-	g
Hydrogen	119.95	172.63	148.32	-	299.42	10^{-3} MJ

In this case, BioGrace carries out a substitution-like procedure in the hydrogenation step of palm oil. Considering this, electricity and natural gas are produced as co-products and are presented as "negative" inputs. GHGenius has the highest natural gas inputs among the models assessed in this study. New EC considers no external H_2 inputs because this model considers the NExBTL process, including on-site H_2 generation, for the production of a BTL-like fuel. Finally, while the VSB model considers no inputs of electricity since it is generated as co-product, it also presents the highest default input of H_2 among the five models.

Palm FFB and palm oil transportation were already presented in Table 18 (please refer to section "Biofuels from palm: FAME"). Regarding cradle-to-pump boundaries, Table 19 indicates the distribution distances among the five assessed models. GREET and New EC split the transportation of HVO/HEFA among different transportation modals. BioGrace and New EC also consider electricity consumption during the distribution process. Finally, only the New EC model takes into account HVO/HEFA distribution overseas. BioGrace, GREET and New EC consider an intermediate terminal before final HVO/HEFA distribution by truck. Modal shares in GREET and New EC are indicated in parentheses in Table 19.

Table 19: Palm HVO/HEFA distribution.

	BioGrace	GHGenius	GREET	New EC	VSB	Unit
Electricity	4.24	-	-	4.24	-	10^{-3} MJ
Truck	150	225	80 (63%)	305 (12%)	300	km
Ocean	-	-	-	1,118 (32%)	-	km
Barge	-	-	837 (8%)	153 (51%)	-	km
Train	-	644	1,288 (29%)	381 (4%)	-	km
Truck (final distribution)	150	-	48	150	-	km

7. UCO biofuels

The main objective of this section is to present a comparison between pre-existing scenarios of UCO biofuels production (FAME and HVO/HEFA) in the LCA models and identification of the particularities leading to different outcomes.

7.1. FAME

Figure 9 presents the boundaries of UCO FAME production for all assessed models. GREET was not included in the analysis since the model presents no default pathway for such feedstock. The cradle-to-gate approach considers the emissions of FAME production up to the gate of the producing unit, while cradle-to-pump boundaries include additional impacts associated to biofuel distribution to fuel pumps.

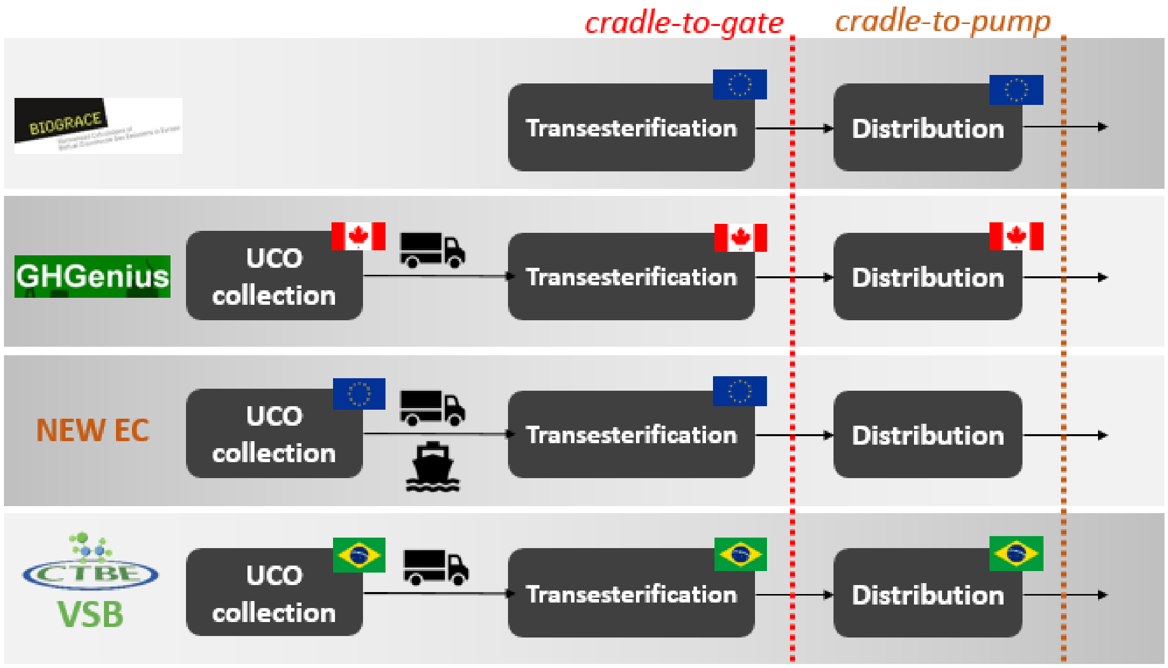

Figure 9: System boundaries - FAME from UCO

BioGrace and New EC consider glycerin and a fraction named "bio-oil" as co-products during FAME production, while GHGenius and VSB only consider glycerin as a co-product. Table 20 presents the transportation modals and distances for UCO collection and transportation. The New EC model considers part of the UCO coming from overseas, while BioGrace considers UCO entering the industrial site with zero associated GHG emissions (residue with zero energy consumption for collection and transportation).

Table 20: UCO collection/transportation

	BioGrace	**GHGenius**	**New EC**	**VSB**	**Unit**
UCO collection					
Truck	-	150	100	300	km
Ocean	-	-	7,000	-	km

The industrial inputs vary significantly among models (Table 21 and Table 22). It is worthwhile highlighting the high energy inputs required for pre-processing process in

GHGenius. Due to a lack of standardization of processing UCO, the VSB model still does not consider a pre-processing step of such feedstock before transesterification. Internal calculations were done with LHV values, except for GHGenius (calculations and process inputs consider HHV values). All final emissions are given in MJ of biofuels (LHV basis).

Table 21: Industrial inputs per MJ of UCO

	BioGrace	GHGenius	New EC	VSB	Unit
UCO pre-processing/refining					
Electricity	1.07	8.65	1.00	-	10^{-3} MJ
Natural gas	12.79	16.28	4.48	-	10^{-3} MJ
H_3PO_4	-	-	0.03	-	g
NaOH	-	-	0.09	-	g
Fuller's earth	0.23	-	-	-	g

Considering the transesterification step, the New EC model is the only one to consider NaOH and H_3PO_4 for the pre-processing of UCO. BioGrace considers Fuller's earth as an input.

Table 22: Industrial inputs per MJ of UCO FAME

	BioGrace	GHGenius	New EC	VSB	Unit
UCO transesterification					
Electricity	5.70	17.53	4.07	4.16	10^{-3} MJ
Natural gas	137.40	122.50	98.15	-	10^{-3} MJ
Coal	-	0.01	-	-	t
Diesel	-	0.01	-	0.01	10^{-3} MJ
Forest resources	-	-	-	35.03	10^{-3} MJ
H_3PO_4	0.55	0.02	0.39	0.01	g
HCl	-	0.33	-	0.37	g
NaOH	-	0.01	-	0.04	g
Citric acid	-	0.02	-	-	g
Nitrogen	-	0.70	-	-	g
Sodium methylate	-	0.18	-	0.62	g
KOH	0.51	-	0.36	-	g
K_2SO_4	-1.00	-	-	-	g
Methanol	84.71	51.80	60.50	58.04	10^{-3} MJ

BioGrace considers a credit for the production of K_2SO_4 in the transesterification step. Also, the model takes into account considerably high inputs of methanol for the conversion of

UCO. GHGenius is the only model to consider nitrogen, citric acid and coal for the transesterification process, despite the amounts of the two last inputs being low. The energy inputs in the VSB model are relatively low, in comparison to the remaining models.

In the case of the cradle-to-pump approach, additional information is considered to analyze the FAME distribution step (Table 23). BioGrace and New EC consider electricity consumption in the distribution step. GREET and New EC split FAME distribution among different transportation modals. Besides, New EC is the only model to consider distribution of FAME overseas. BioGrace and New EC consider an intermediate terminal before final FAME distribution by truck. Table 23 indicates modal shares in GREET and New EC in parentheses.

Table 23: UCO FAME distribution

	BioGrace	GHGenius	New EC	VSB	Unit
Electricity	4.24	-	4.24	-	10^{-3} MJ
Truck	150	132	305 (11%)	300	km
Ocean	-	-	1,118 (27%)	-	km
Barge	-	-	153 (44%)	-	km
Train	-	-	381 (4%)	-	km
Truck (final distribution)	150	-	150	-	km

7.2. HVO/HEFA

The production of HVO/HEFA from UCO varies among models (

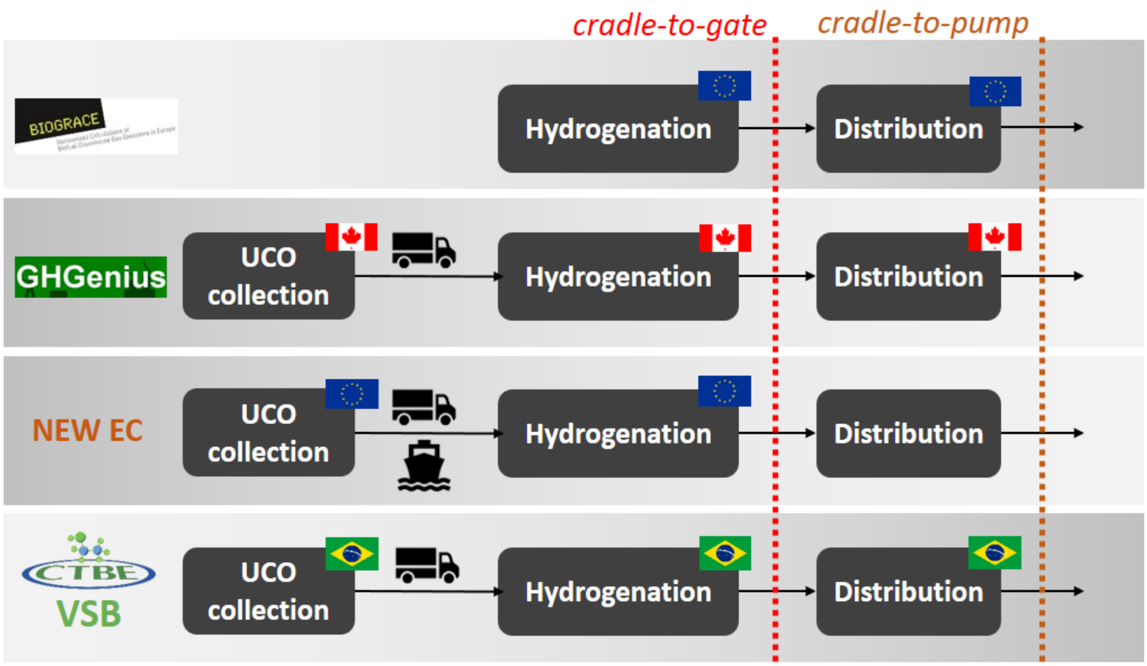

Figure 10). System boundaries are the same as those considered for FAME from UCO. It is worthwhile mentioning that BioGrace has no pathway for HVO/HEFA production from UCO. This pathway was created considering the inputs for UCO collection and extraction retrieved from FAME production, while those concerning oil hydrogenation were obtained from the default conversion of palm oil.

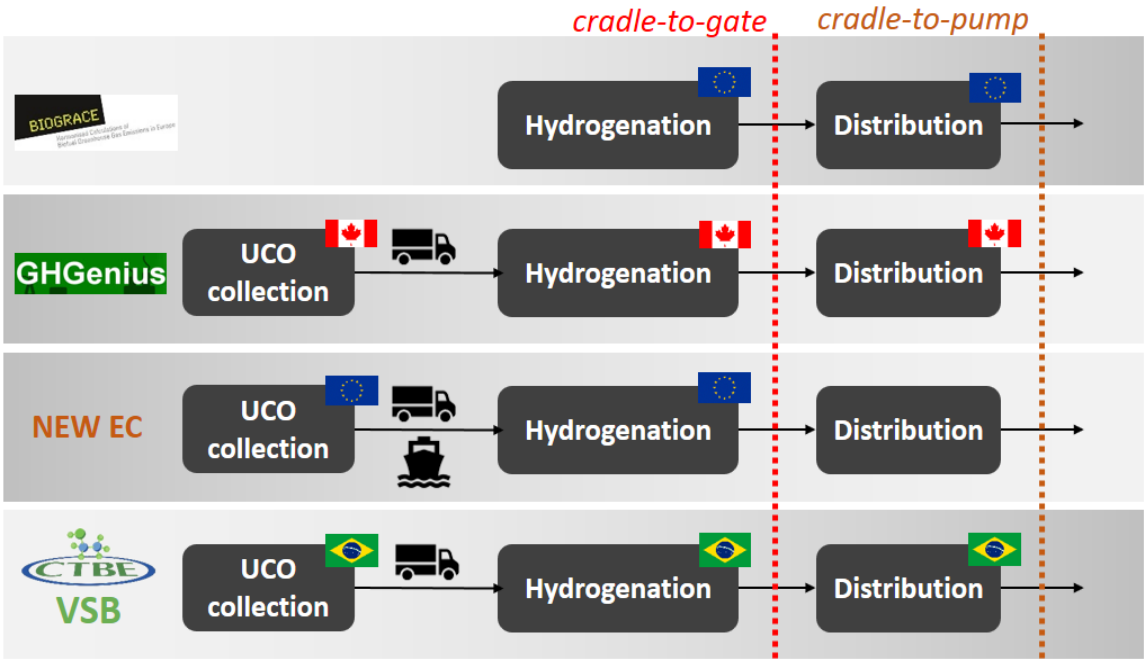

Figure 10: System boundaries - HVO/HEFA from UCO

Differently from FAME, the co-products from HVO/HEFA production processes vary significantly among models. Table 24 presents the co-products considered in each model. Again, the GHGenius model does not specify the nature of co-products "Other gaseous" and "Other liquids".

Table 24: Products and co-products from UCO HVO/HEFA

	BioGrace	GHGenius	New EC	VSB
Main product	HVO	Hydrotreated Renewable Jet Fuel (HRJ)	HVO (diesel-like molecule)	Biojet Fuel
Co-products	Natural gas; Electricity	"Other gaseous"; "Other liquids"	Gasoline	Renewable gasoline; Renewable diesel; Electricity

UCO oil is considered to be pre-processed before hydrogenation in all models, except for the VSB. All process inputs regarding UCO collection were presented in Table 21 (please refer to section “UCO biofuels: FAME”), while the inputs for hydrogenation of UCO are shown in Table 25. Internal calculations were done with LHV values, except for GHGenius (calculations and process inputs consider HHV values). All final emissions are given in MJ of biofuels (LHV basis).

Table 25: Industrial inputs per MJ of UCO HVO/HEFA

	BioGrace	GHGenius	New EC	VSB	Unit
UCO hydrogenation					
Electricity	-2.11	6.06	1.55	-	10^{-3} MJ
Natural gas	-12.37	254.66	109.81	-	10^{-3} MJ
Diesel	-	0.02	-	0.02	10^{-3} MJ
Forest resources	-	-	-	37.55	10^{-3} MJ
H_3PO_4	-	0.02	0.02	-	g
NaOH	-	0.03	0.03	-	g
Nitrogen	-	-	0.01	-	g
Hydrogen	119.95	172.63	-	239.99	10^{-3} MJ

In this case, BioGrace carries out a substitution-like procedure in the hydrogenation step of soybean oil. Considering this, electricity and natural gas are produced as co-products and are presented as “negative” inputs. New EC considers no external H_2 input in view of the base process (NExBTL) including on-site H_2 generation. Besides, the model is the only to consider nitrogen inputs, however in a low amount. The VSB model considers no external inputs of electricity since it is generated as co-product in the industrial step. Energy inputs in this model are low in comparison to the remaining ones. It also takes into account the highest input of H_2 among the studied models. Inputs for UCO collection and transportation were presented in Table *20* (please refer to section “Biofuels from UCO: FAME”).

Regarding a cradle-to-pump approach, Table 26 shows the distribution distances among the four assessed models. Again, New EC splits biofuel distribution among different transportation modals. BioGrace and New EC consider electricity consumption during distribution process, while only New EC considers HVO/HEFA distribution overseas. BioGrace and New EC consider an intermediate terminal before final FAME distribution by truck. Modal shares in GREET and New EC are indicated in parentheses (Table 26).

Table 26: UCO HVO/HEFA distribution

	BioGrace	GHGenius	New EC	VSB	
Electricity	4.24	-	4.24	-	10-3 MJ
Truck	150	225	305 (11%)	300	km
Ocean	-	-	1,118 (27%)	-	km
Barge	-	-	153 (44%)	-	km
Train	-	644	381 (4%)	-	km
Truck (final distribution)	150	-	150	-	km

8. Harmonization between LCA models using VSB data and parameters

For this study, default data and parameters were retrieved from the VSB database and entered on three other models (BioGrace/GHGenius/GREET) for harmonization purposes - the New EC model was not included in the harmonization since the calculation procedures are proprietary and, therefore, not publicly available to users. With this approach, it was possible, for each scenario, to identify the main differences and to check the possibility of reaching similar impacts from different LCA models considering the same production system. Besides, this approach helps understanding if the LCA models are consistent regarding their methodology and system boundaries. This analysis of climate change impact was only performed for the soybean/FAME duo and considering a cradle-to-gate approach (FAME distribution was not harmonized).

The following list of items was taken into account in the harmonization exercise:

- Agricultural inputs and industrial inputs (oil extraction and oil transesterification);
- Soybean productivity and industrial yields;
- Insertion of transportation modals and distances considered in the VSB model;
- Removal of overseas soybean transportation in the BioGrace model;
- Modification of default methods to consider full economic allocation as in VSB;
- Insertion of VSB emission factors for selected inputs with discrepant values: NPK fertilizer, diesel, and methanol (which have the highest influence over the final result);

- Removal of BioGrace 1.4 factor for converting input values from typical to default in industrial processes (oil extraction and oil transesterification).

Results are presented in Section 10.

9. Results: comparison of LCA models

9.1. Biofuels from soybean oil

The main objective of this section is to present a comparison between the emissions of the pre-existing scenarios of soybean biofuels production (FAME and HVO/HEFA) in the LCA models and identification of the particularities leading to different outcomes.

9.1.1. Soybean production emissions

This section details the findings limited to the agricultural step of soybean production. Figure 11 presents the emissions associated with soybean production in the five assessed models in terms of g of CO_2eq per kg of soybean (dry basis).

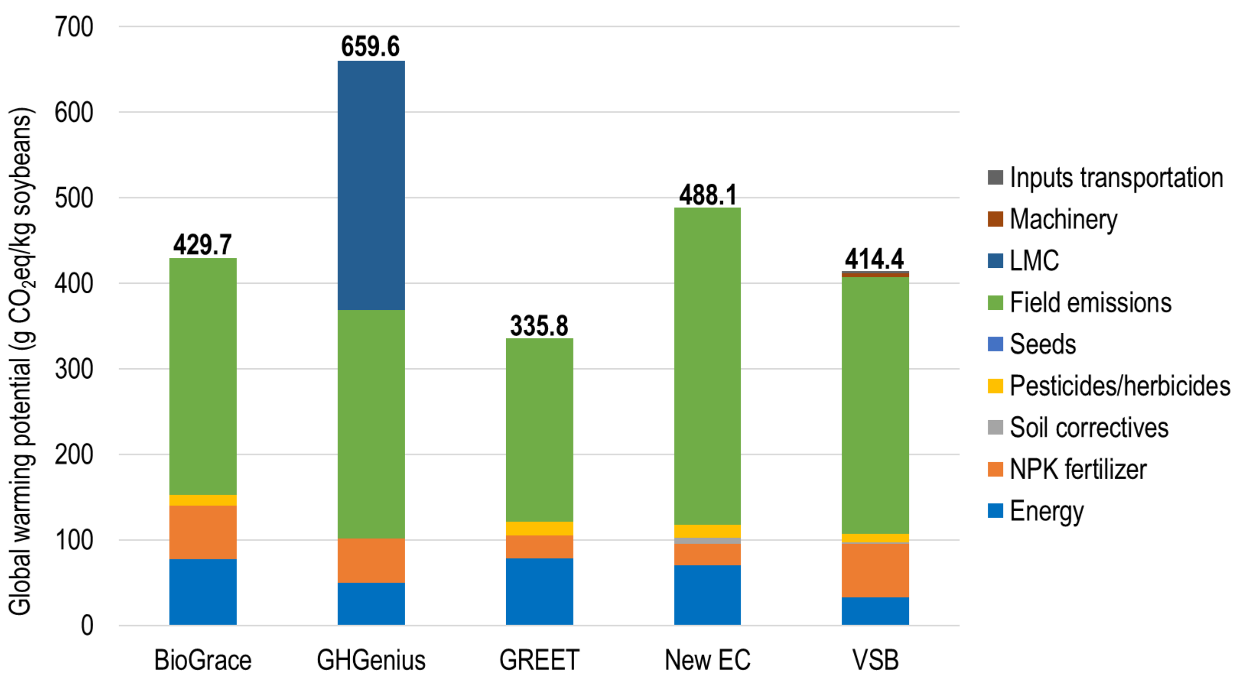

Figure 11: Soybean agricultural emissions

BioGrace and VSB present relatively close results for the agricultural step of soybean production, since both models consider input values for a hypothetical Brazilian production system. GHGenius is the only model to consider LMC emissions representing soil carbon emissions or sinks from changes in tillage practices, cropping intensity, and annuals vs perennials. Most emissions refer to a transition between perennial to annual crops. GREET has low emissions associated with NPK application due to a significantly lower consumption of mineral fertilizers in comparison to either BioGrace, New EC or VSB. The GHGenius model has a similarly low default input of mineral fertilizers in comparison to GREET. Part of the differences between GREET and GHGenius concerning energy use can be explained through the use of irrigation in the USA and the cultivation without irrigation in Canada. In New EC, emissions from soil correctives are high in view of considerably high inputs to correct soil acidity. Finally, the VSB is the only model to consider emissions associated to machinery and inputs transportation.

9.1.2. Soybean FAME emissions

9.1.2.1. Cradle-to-gate

In the cradle-to-gate approach, emissions from FAME production include:

- Cultivation of soybean (Figure 11);
- Soybean transportation to the extraction plant;
- Extraction process;
- Soybean oil transportation to the transesterification plant (presented together with soybean transportation);
- Transesterification process;
- Emissions displaced by co-products.

Emissions are presented in g of CO_2eq per MJ of FAME (Table 27 and Figure 12), according to the allocation method of each model, or substitution method as in GHGenius.

Table 27: Cradle-to-gate emissions associated with soybean FAME production in g CO_2eq/MJ FAME, by production step

	BioGrace	GHGenius	GREET	New EC	VSB
Cultivation of soybean	18.50	94.99	17.27	21.07	19.24
Extraction	8.61	13.34	6.98	3.41	0.42
Transesterification	16.75	3.65	8.25	8.90	3.56
Transportation (soybean and oil)	11.83	2.05	1.51	7.60	1.09
Emissions displaced by co-products	-	-98.33*	-	-	-
Total	**55.68**	**15.70**	**34.01**	**40.97**	**24.30**

*soybean meal: -88.53 and glycerin: -9.80

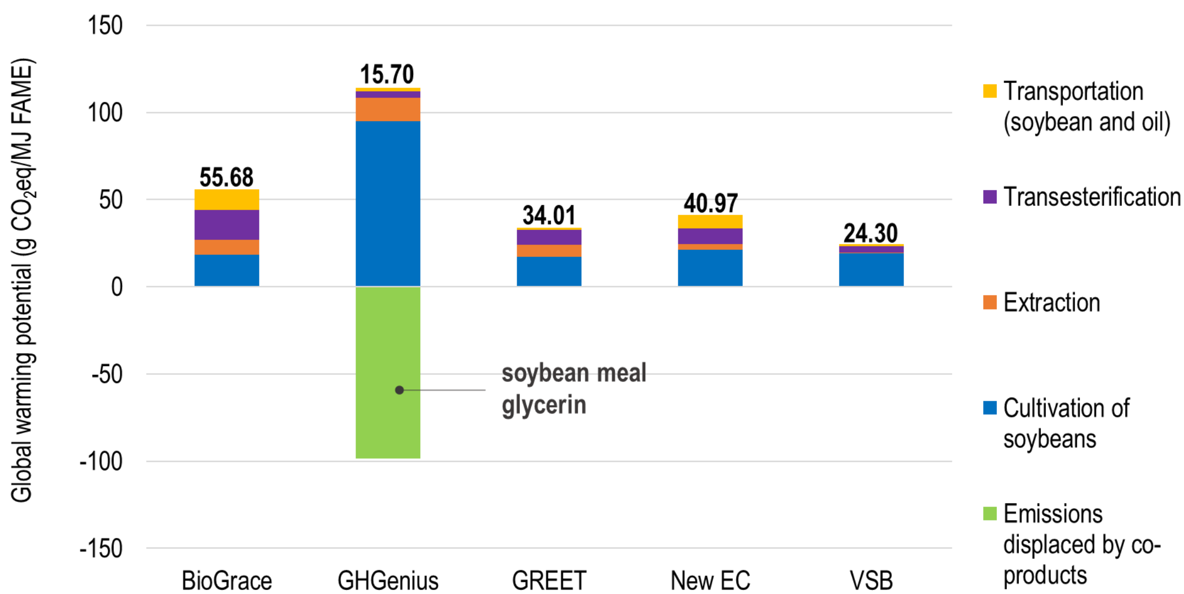

Figure 12: Cradle-to-gate emissions of soybean FAME production

The BioGrace model considers a 1.4 factor for converting input values from typical to default in industrial processes (oil extraction and oil transesterification). Soybean transportation emissions are high since the model considers overseas transportation of soybean from Brazil to the EU for processing. The model also considers energy allocation. GHGenius does not allocate emissions, but rather considers co-products credits (substitution procedure). In view of this, soybean cultivation presents higher emissions that in other models, although the final emissions per MJ of FAME are considerably lower than other models due to high credits given to co-products. Results for the soybean FAME pathway in GREET consider full energy allocation, although mass allocation for oil extraction and economic allocation for FAME production are the default methods. In New EC, soybean transportation emissions are relatively high since the model considers 90% of the soybean coming from overseas (Argentina, Brazil, and USA). The determined value of 40.97 g CO_2eq/MJ FAME was calculated with the BioGrace model using New EC input data in the BioGrace calculation tool, while the default value in New EC is of 42.40 g CO_2eq/MJ FAME. There are several possible reasons for the remaining (small) differences in the calculated values, such as specific physical properties (density, LHV, among others), palm productivity (this point is a required input in the BioGrace calculation tool), specific emission factors (such as those of heating oil and HFO for maritime transport), and inclusion of back-haul in transportation (this reasoning also applies to soybean HVO/HEFA and palm biofuels pathways). Finally, the VSB considers the consumption of high amounts of renewable energy in the industrial phase (oil extraction and transesterification), thus leading to lower associated emissions. The model employs economic allocation. The final emission per MJ of soybean FAME varies considerably among models. GREET and New EC are the only two models to present similar results.

9.1.2.2. Cradle-to-pump

Using cradle-to-pump boundaries, emissions from FAME production include those previously reported in the cradle-to-gate analysis plus the emissions from fuel storage and distribution:

- Cultivation of soybean (Figure 11);
- Soybean transportation to the extraction plant;
- Extraction process;

- Soybean oil transportation to the transesterification plant (presented together with soybean transportation);
- Transesterification process;
- Emissions displaced by co-products;
- FAME storage and distribution.

Emissions are presented in g of CO_2eq per MJ of FAME (Table 28 and Figure 13), according to the allocation method of each model, or substitution method as in GHGenius.

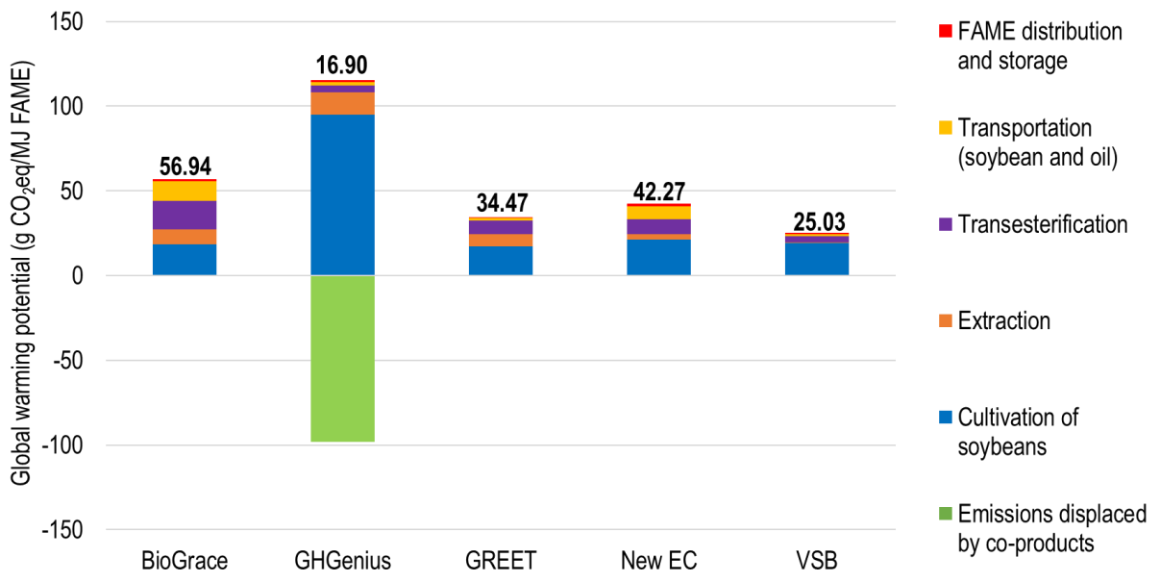

Table 28: Cradle-to-pump emissions associated with soybean FAME production in g CO_2eq/MJ FAME, by step of production

	BioGrace	**GHGenius**	**GREET**	**New EC**	**VSB**
Cultivation of soybean	18.50	94.99	17.27	21.07	19.24
Extraction	8.61	13.34	6.98	3.41	0.42
Transesterification	16.75	3.65	8.25	8.90	3.56
Transportation (soybean and oil)	11.83	2.05	1.51	7.60	1.09
Emissions displaced by co-products	-	-98.33	-	-	-
FAME distribution and storage	1.26	1.20	0.46	1.30	0.73
Total	56.94	16.90	34.47	42.27	25.03

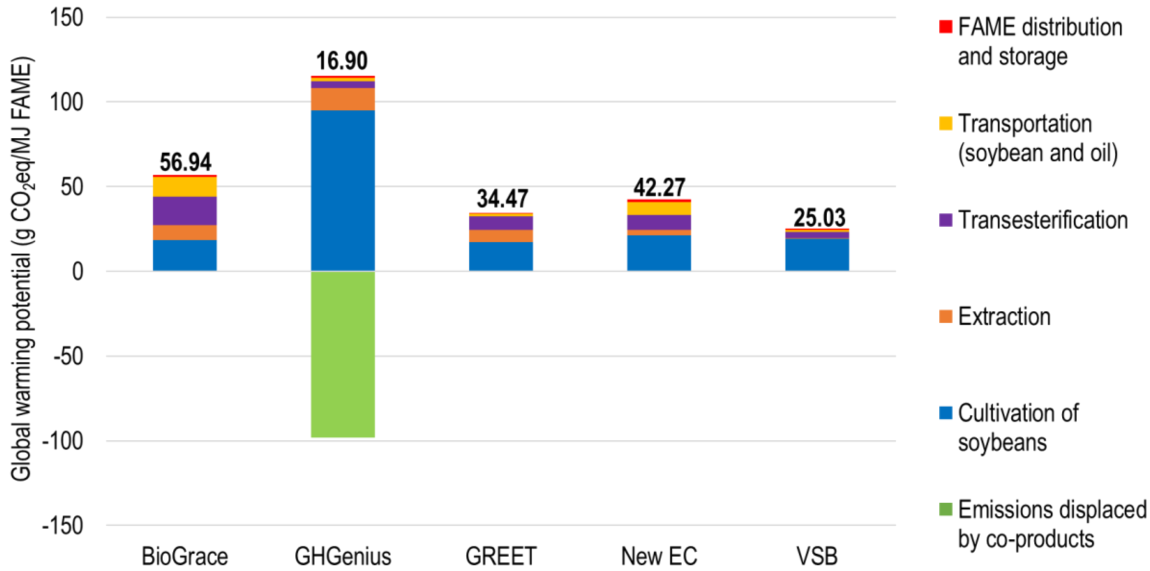

Figure 13: Cradle-to-pump emissions of soybean FAME production

BioGrace, GHGenius and New EC present similar results for FAME distribution. The GREET model simulates FAME production in the USA and for domestic consumption; therefore, emissions associated with transportation are low. The VSB model, as in the case of GREET, considers FAME production in Brazil and for Brazilian domestic consumption.

Final remarks for soybean FAME

As final remarks for soybean FAME emissions, Table 29 summarizes the overall findings of the analysis.

Table 29: Final remarks of model analysis for soybean FAME production

	BioGrace	GHGenius	GREET	New EC	VSB
Agricultural phase	High energy input	High amount of LMC emissions	High consumption of natural gas	High N_2O field emissions	High K_2O and $CaCO_3$ consumption; high CO_2 field emissions
Industrial phase	Only model to consider oil refining. High consumption of natural gas, high use of methanol and electricity	High emissions associated with oil extraction. High n-hexane consumption	Emission factors for natural gas, electricity, coal and n-hexane are high	Only model to consider pre-drying steps for soybean conditioning	Low fossil fuel consumption and to electricity in Brazil being largely of renewable origin
Transportation (soybean and oil)	High emissions due to large transportation distances	Low emissions	Low emissions	High emissions due to large transportation distances	Low emissions
Distribution	High emissions associated with distribution	High emissions associated with distribution	Low emissions	High emissions associated with distribution	Low emissions
Global warming potential	High emissions	Low emissions due to high co-product's credits (soybean meal and glycerin)	Intermediate emissions compared to the other models	Intermediate emissions compared to the other models	Low emissions due to low fossil energy consumption

9.1.3. Soybean HVO/HEFA emissions

The results for HVO/HEFA emissions from soybean are presented in a similar fashion to that of soybean FAME emissions.

9.1.3.1. Cradle-to-gate

In the cradle-to-gate approach, emissions from HVO/HEFA production include:

- Cultivation of soybean (Figure 11);
- Soybean transportation to the extraction plant;
- Extraction process;
- Soybean oil transportation to the transesterification plant (combined with soybean transportation);
- Hydrogenation process;
- Emissions displaced by co-products.

Emissions are presented in g of CO_2eq per MJ of HVO/HEFA (Table 30 and Figure 14), according to the allocation method of each model, or substitution method as in GHGenius.

Table 30: Cradle-to-gate emissions associated with soybean HVO/HEFA production in g CO_2eq/MJ HVO/HEFA, by step of production

	BioGrace	GHGenius	GREET	New EC	VSB
Cultivation of soybean	19.08	136.60	18.58	21.73	20.33
Extraction	8.87	19.19	7.50	3.52	0.44
Hydrogenation	9.34	16.83	19.42	7.46	2.92
Transportation (soybean and oil)	12.20	2.95	1.63	7.83	1.15
Emissions displaced by co-products	-	-128.01*	-	-	-
Total	**49.48**	**47.55**	**47.12**	**40.54**	**24.83**

*soybean meal: -92.29; other gaseous and other liquids: -23.67 and –12.05, respectively

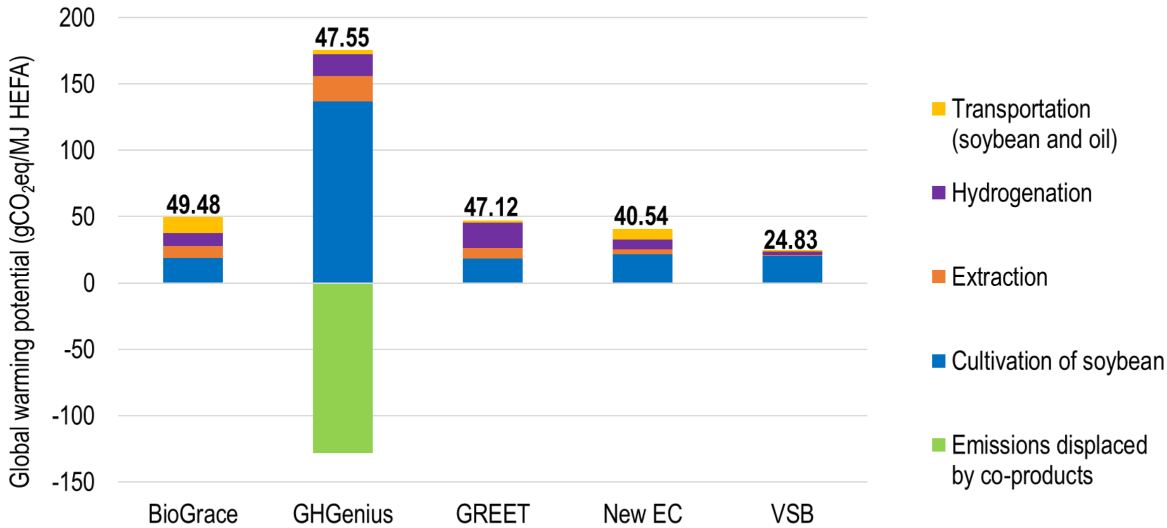

Figure 14: Cradle-to-gate emissions of soybean HVO/HEFA production

BioGrace considers a 1.4 factor for converting selected inputs in the industrial step from typical to default (oil extraction and oil transesterification). As in the case of soybean FAME, emissions associated to soybean transportation are high since the model considers overseas transportation of the grain from Brazil to the EU. The BioGrace model considers energy allocation. The GHGenius model employs a substitution procedure to account for co-products obtained in the industrial step. GREET uses mass allocation in the oil extraction step and energy allocation in HVO/HEFA production. In the New EC model, soybean transportation emissions are high since the biofuel chain considers 90% of soybean coming from overseas (Argentina, Brazil, and USA). The determined value of 40.54 g CO_2eq/MJ HVO/HEFA was estimated with the BioGrace model using New EC input data and full energy allocation, while the default value in New EC is of 42.20 g CO_2eq/MJ HVO/HEFA. Finally, the VSB model considers the consumption of high amounts of renewable energy in the industrial phase (oil extraction and transesterification) and employs full economic allocation.

The determined emissions for soybean HVO/HEFA production are still variable among the five models, however less discrepant than in the case of soybean FAME. BioGrace, GHGenius and GREET present relatively similar results.

Cradle-to-pump

In the cradle-to-pump approach, emissions from HVO/HEFA production include those previously reported using cradle-to-gate boundaries, plus emissions from fuel storage and distribution:

- Cultivation of soybean (Figure 11);
- Soybean transportation to the extraction plant;
- Extraction process;
- Soybean oil transportation to the transesterification plant (presented together with soybean transportation);
- Hydrogenation process;
- Emissions displaced by co-products;
- HVO/HEFA storage and distribution.

Emissions are presented in g of CO_2eq per MJ of HVO/HEFA (Table 31 and Figure 15), according to the allocation method of each model, or substitution method as in GHGenius.

Table 31: Cradle-to-pump emissions associated with soybean HVO/HEFA production in g CO_2eq/MJ HVO/HEFA, by step of production

	BioGrace	GHGenius	GREET	New EC	VSB
Cultivation of soybean	19.08	136.60	18.58	21.73	20.33
Extraction	8.87	19.19	7.50	3.52	0.44
Hydrogenation	9.34	16.83	19.42	7.46	2.92
Transportation (soybean and oil)	12.20	2.95	1.63	7.83	1.15
Emissions displaced by co-products	-	-128.01	-	-	-
HVO/HEFA distribution and storage	1.15	1.03	0.45	1.40	0.63
Total	**50.63**	**48.58**	**47.57**	**41.94**	**25.46**

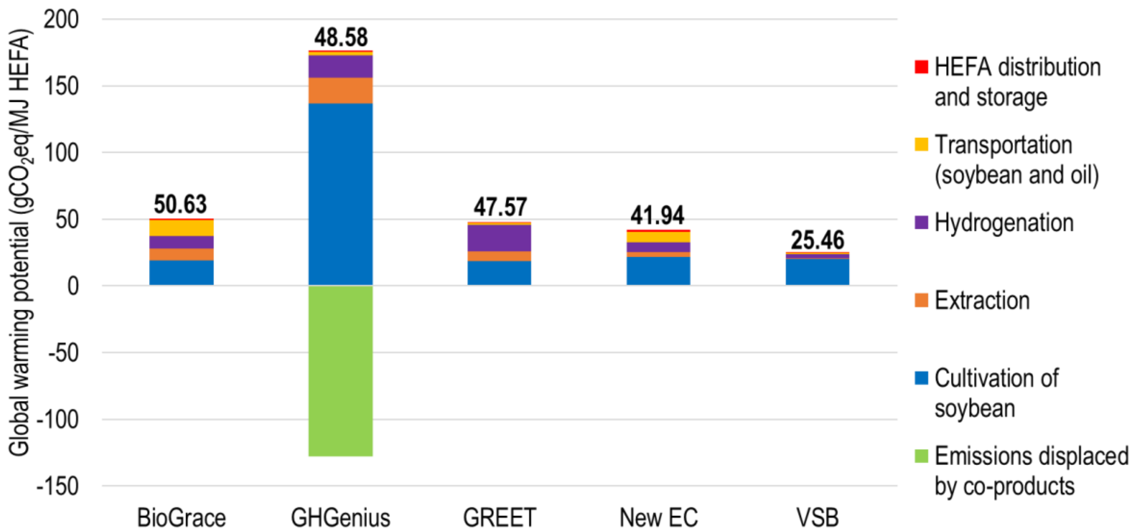

Figure 15: Cradle-to-pump emissions of soybean HVO/HEFA production

As in the case of soybean FAME storage and distribution, the emissions associated to the storage and distribution of HVO/HEFA vary among the five assessed models.

Final remarks for soybean HVO/HEFA

Table 32 presents a summary of the main points related to each production step in the five assessed models.

Table 32: Final remarks of model analysis for soybean HVO/HEFA production

	BioGrace	GHGenius	GREET	New EC	VSB
Agricultural phase	High energy input	High amount of LMC emissions	High consumption of natural gas	High N_2O field emissions	High K_2O and $CaCO_3$ consumption; high CO_2 field emissions
Industrial phase	Only model to consider oil refining. High consumption of natural gas, high use of methanol and electricity.	High emissions associated with oil extraction. High n-hexane consumption	Emission factors for natural gas, electricity, coal and n-hexane are high. Considers coal consumption	Only model to consider pre-drying steps for soybean conditioning	Low emissions due to low fossil fuel consumption (e.g. H_2 production through thermal cracking of petroleum heavy oil)
Transportation (soybean and oil)	High emissions due to large transportation distances	Low emissions	Low emissions	High emissions due to large transportation distances	Low emissions
Distribution	High emissions associated with distribution	High emissions associated with vehicle operation	Low emissions	High emissions associated with distribution	Low emissions
Global warming potential	High emissions	High emissions	High emissions	Intermediate emissions compared to the other models	Low emissions due to low fossil energy consumption

9.2. Biofuels from palm oil

The main objective of this section is to present a comparison between the emissions of default scenarios of palm biofuels production (FAME and HVO/HEFA) in the five studied LCA models and identification of the particularities leading to different outcomes.

9.2.1. Palm production emissions

Figure 16 presents the emissions associated with palm production in each model. The results are presented in g of CO_2eq per kg of palm FFB (dry basis).

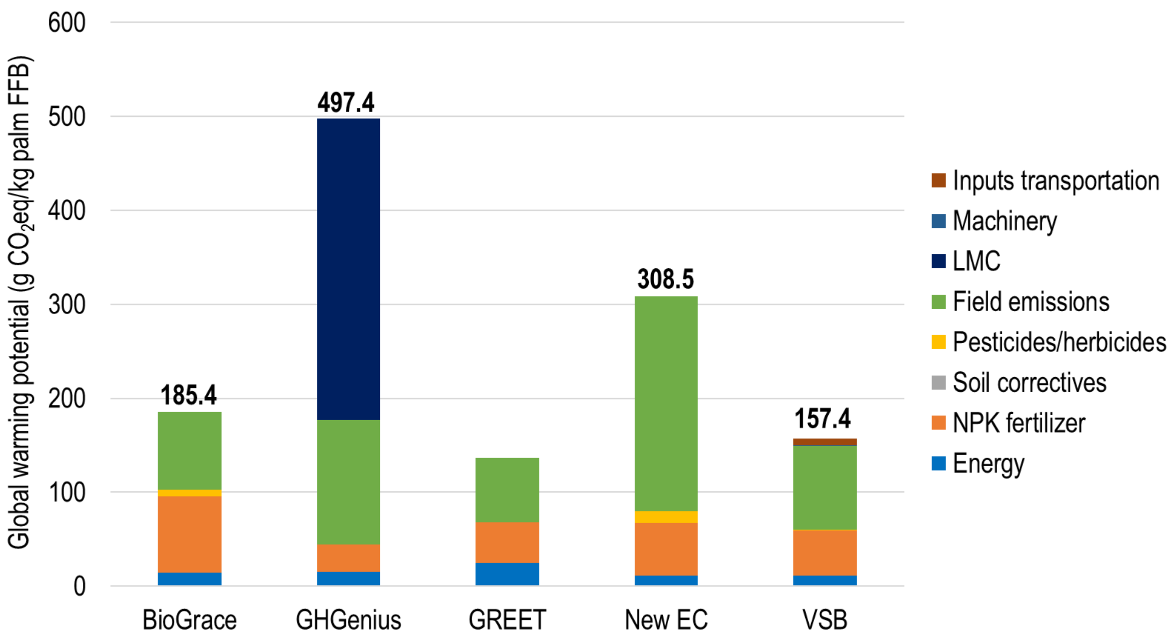

Figure 16: Palm agricultural emissions

BioGrace presented high emissions associated to the use of mineral fertilizers, which agrees with the high consumption of such inputs in the model. In GHGenius, extremely high LMC correspond mostly to CO_2 emissions from draining the peat soils on which palm is often planted. Such emissions occur year after year as the peat soil subsides and none of the other models consider them. GREET is the most energy intensive model for palm agricultural production, consuming the largest quantities of diesel in the agricultural phase. The New EC model includes the highest emissions associated with pesticides/herbicides application, while the VSB is the only model to consider emissions associated to machinery and inputs transportation.

The results from BioGrace, GREET and VSB are similar, while GHGenius presents a considerably higher than the remaining results mainly in view of the inclusion of LMC emissions to the result. It can also be observed that the estimated emission would remain at around 170 g CO_2eq per kg of palm FFB if such component is removed from the calculations.

9.2.2. Palm FAME emissions

9.2.2.1. Cradle-to-gate

In the cradle-to-gate approach, emissions from FAME production include:

- Cultivation of palm (Figure 16);
- Palm transportation to extraction plant;
- Extraction process;
- Palm oil transportation to transesterification plant (presented together with palm transportation);
- Transesterification process;
- Emissions displaced by co-products.

Emissions are presented in g of CO_2eq per MJ of FAME (

Table *33* and Figure 17), according to the allocation method of each model, or substitution method as in GHGenius. In Figure 17, results for BioGrace and New EC are presented for two slightly different industrial configurations each: with capture ("*cpt*") and without capture ("*no cpt*") of CH_4 emissions from the POME pond. Such emissions are located in the industrial phase of the production chain (palm oil extraction from FFB).

Table 33: Cradle-to-gate emissions associated with palm FAME production in g CO_2eq/MJ FAME, by step of production

	BioGrace		GHGenius	GREET	New EC		VSB
	No cpt	Cpt			No cpt	Cpt	
Cultivation of FFB	14.19	14.19	59.64	10.60	23.33	23.33	16.54
Extraction	30.03	1.01	19.70	1.19	18.99	3.15	1.66
Transesterification	16.75	16.75	3.65	8.31	9.50	9.50	3.56
Transportation (palm and oil)	3.74	3.74	2.78	3.35	4.75	4.75	7.26
Emissions displaced by co-products	-	-	-10.50*	-	-	-	-
Total	**64.70**	**35.68**	**75.26**	**23.45**	**56.57**	**40.73**	**29.02**

*palm meal: -1.11; glycerin: -9.39

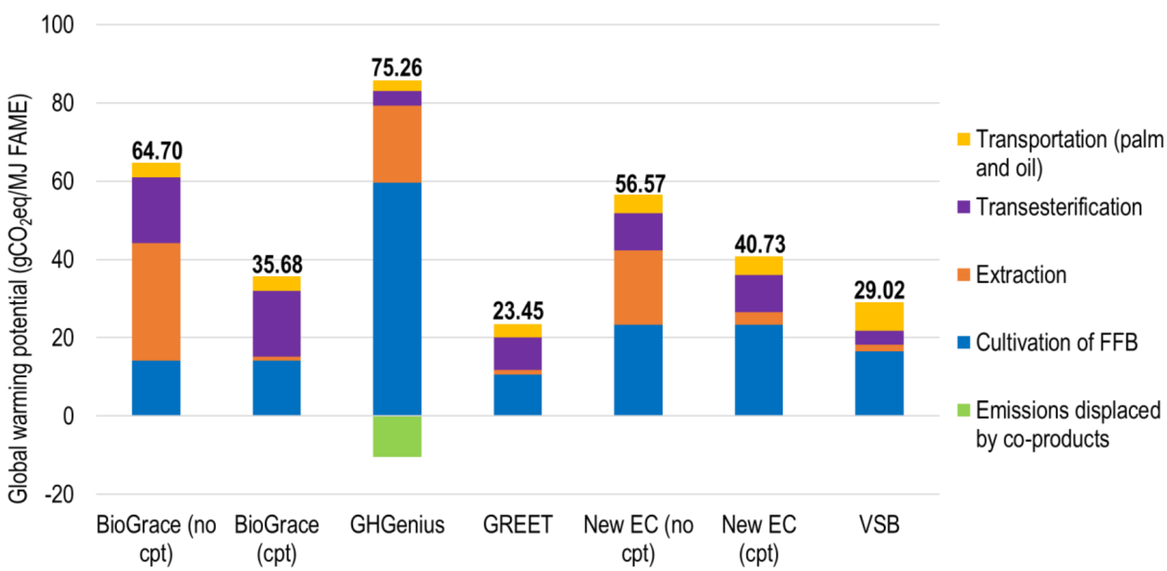

Figure 17: Cradle-to-gate emissions of palm FAME production

Cpt: with CH_4 capture from POME
No cpt: without CH_4 capture from POME

BioGrace considers a 1.4 factor for converting selected input values from typical to default in industrial processes (oil extraction and oil transesterification). The oil extraction process in BioGrace (without CH_4 capture) is the most energy-intensive one among the studied models. As for soybean-based systems, the model also uses full energy allocation. The GHGenius model does not allocate emissions, but rather considers co-products credits (substitution). In view of this, palm cultivation presents higher emissions that in other models. The pathway in GREET was built in the software from pre-existing (default) data for palm cultivation and transportation combined with data from soybean oil transesterification. The GREET database informs that palm oil extraction is carried out with CH_4 capture from POME and the models employs energy allocation in oil extraction and economic allocation in FAME production. Regarding the New EC model, this study determined values of 40.73 g CO_2eq/MJ FAME and 56.57 g CO_2eq/MJ FAME for processes with and without CH_4 capture, respectively, through using the BioGrace model with New EC input data. The default values in New EC are 40.80 g CO_2eq/MJ FAME (with CH_4 capture) and 58.00 g CO_2eq/MJ FAME (without CH_4 capture). The VSB is the only model to consider palm production in Brazil; despite not considering overseas transportation of palm oil, emissions related to transportation steps are relatively high in view of the distance (2,000 km) covered by trucks.

In general, emissions per MJ of FAME produced from palm oil vary among the five models assessed. GREET and VSB present the lowest emissions, mainly due to low inputs of energy during oil extraction.

9.2.2.2. Cradle-to-pump

In the cradle-to-pump approach, emissions from FAME production include the reported previously in cradle-to-gate approach, plus emissions from fuel storage and distribution:

- Cultivation of palm (Figure 16);
- Palm transportation to the extraction plant;
- Extraction process;
- Palm oil transportation to the transesterification plant (presented together with soybean transportation);
- Transesterification process;
- Emissions displaced by co-products;

- FAME storage and distribution.

Emissions are presented in g of CO_2eq per MJ of FAME (Table 34 and Figure 18), according to the allocation method of each model, or substitution method as in GHGenius.

Table 34: Cradle-to-pump emissions associated with palm FAME production in g CO_2eq/MJ FAME, by step of production

	BioGrace		**GHGenius**	**GREET**	**New EC**		**VSB**
	No cpt	**Cpt**			**No cpt**	**Cpt**	
Cultivation of FFB	14.19	14.19	59.64	10.60	23.33	23.33	16.54
Extraction	30.03	1.01	19.70	1.19	18.99	3.15	1.66
Transesterification	16.75	16.75	3.65	8.31	9.50	9.50	3.56
Transport	3.74	3.74	2.78	3.35	4.75	4.75	7.26
Emissions displaced by co-products	-	-	-10.50	-	-	-	-
FAME distribution and storage	1.26	1.26	1.23	0.46	1.40	1.50	0.73
Total	**65.96**	**36.94**	**78.21**	**24.15**	**57.97**	**42.23**	**30.78**

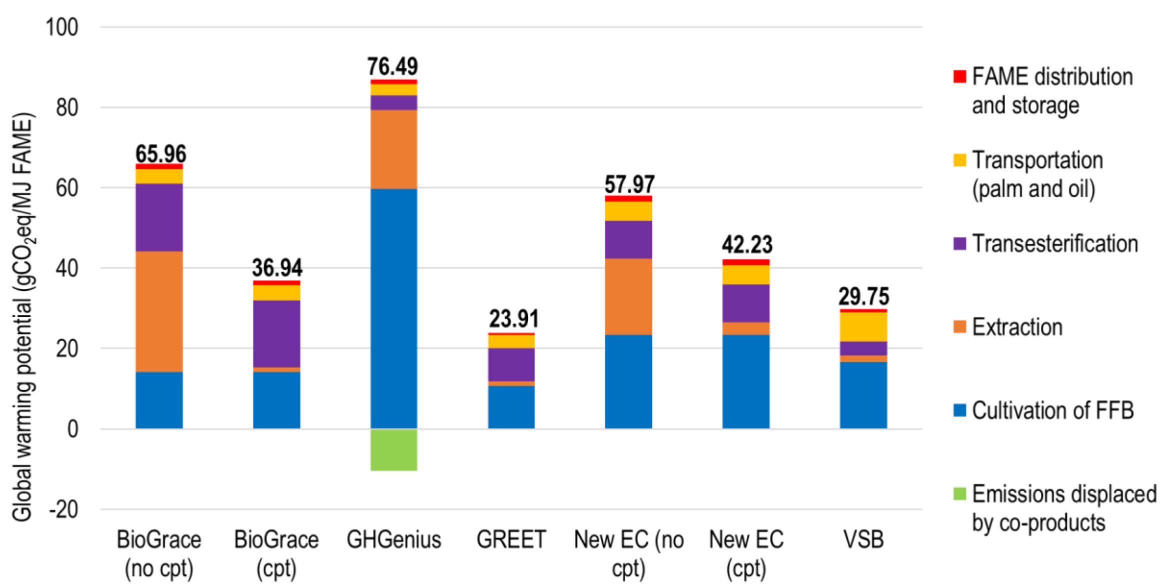

Figure 18: Cradle-to-pump emissions of palm FAME production

The models are similar in the distribution process, except for GREET and VSB (both models simulate FAME production for domestic consumption).

Final remarks for palm FAME

Table 35 summarizes the main points associated to palm FAME production.

Table 35: Final remarks of model analysis for palm FAME production

	BioGrace	GHGenius	GREET	New EC	VSB
Agricultural phase	Considers EFB compost from palm oil for palm FFB production	High emissions from land use change	Low emissions, low requirement of inputs	High amount of N_2O emissions	High amount of "other field emissions"
Industrial phase	Model is able to consider CH_4 capture. Considers oil refining.	Low emissions	Intermediate emissions	Model is able to consider CH_4 capture. Considers oil refining.	Low consumption of fossil fuel
Transportation (palm FFB and oil)	Intermediate emissions	Low emissions	Intermediate emissions	Intermediate emissions	High emissions due to large distances and use of truck modal
Distribution	High emissions associated with distribution	High emissions associated with distribution	Low emissions	Intermediate emissions	Low emissions
Global warming potential	High emissions, if CH_4 capture from POME is not considered	High emissions due to high amount of LUC emissions, but credits from co-products are not as large as for soybean	Low emissions	High emissions, if CH_4 capture from POME is not considered	Low fossil fuel energy consumption

9.2.3. Palm HVO/HEFA emissions

The results for the emissions associated to palm HVO/HEFA are presented in a similar fashion to that of the palm FAME pathway.

9.2.3.1. Cradle-to-gate

In the cradle-to-gate approach, emissions from HVO/HEFA production include:

- Cultivation of palm (Figure 16);
- Palm transportation to the extraction plant;
- Extraction process;
- Palm oil transportation to the transesterification plant (presented together with palm transportation);
- Hydrogenation process;
- Emissions displaced by co-products.

Emissions are presented in g of CO_2eq per MJ of HVO/HEFA (Table 36 and Figure 19), according to the allocation method of each model, or substitution method as in GHGenius. As in the previous section, results for BioGrace and New EC are presented for either with capture ("*cpt*") and without capture ("*no cpt*") of CH_4 emissions from the POME pond.

Table 36: Cradle-to-gate emissions associated with palm HVO/HEFA production in g CO_2eq/MJ HVO/HEFA, by step of production

	BioGrace		GHGenius	GREET	New EC		VSB
	No cpt	Cpt			No cpt	Cpt	
Cultivation of FFB	14.64	14.64	85.77	11.59	24.24	24.24	18.35
Extraction	29.92	0.00	28.33	1.29	19.73	3.27	1.84
Hydrogenation	9.34	9.34	16.83	20.51	5.79	5.79	2.69
Transportation (palm and oil)	3.85	3.85	3.99	3.67	4.93	4.93	8.06
Emissions displaced by co-products	-	-	-36.89*	-	-	-	-
Total	**57.74**	**27.82**	**98.03**	**37.05**	**54.69**	**38.23**	**30.94**

*palm meal: -1.16; other gaseous and other liquids liquids: -23.67 and –12.05, respectively

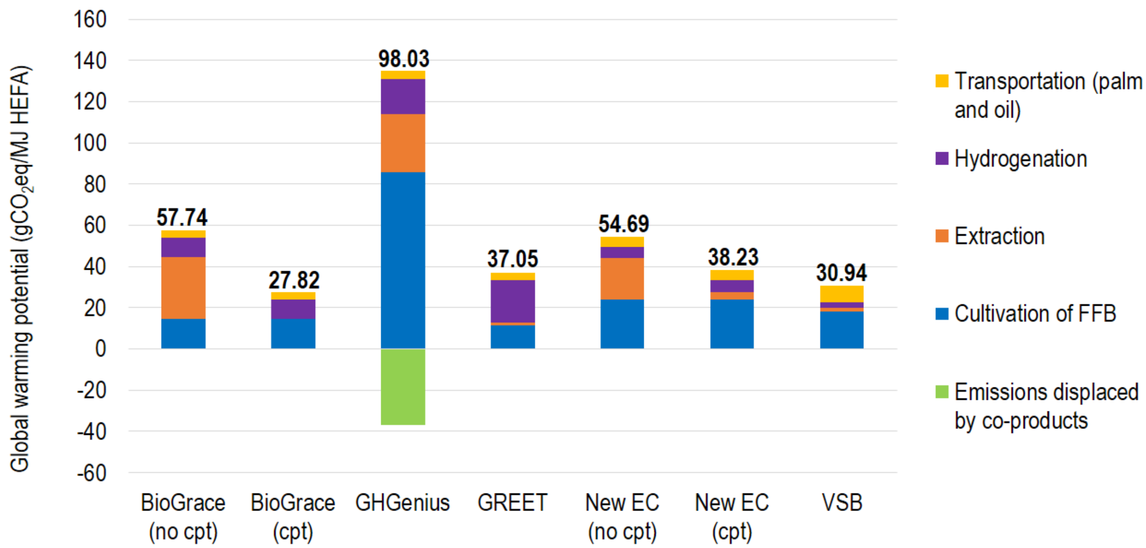

Figure 19: Cradle-to-gate emissions of palm HVO/HEFA production

Cpt: with CH_4 capture from POME
No cpt: without CH_4 capture from POME

BioGrace considers a 1.4 factor for converting input values from typical to default in industrial processes (oil extraction and oil transesterification). In GHGenius, co-products from palm HVO/HEFA do not account for high credits as in the case of soybean biofuels, and, therefore, emissions associated with biofuel production from palm are high when compared to the other models. GREET considers energy allocation in oil extraction and energy allocation in HVO/HEFA production. Hydrogenation in GREET in the most energy-intensive one among the models. Regarding New EC, the determined values of 38.23 g CO_2eq/MJ HVO/HEFA and 54.69 g CO_2eq/MJ HVO/HEFA for processes with and without CH_4 capture, respectively, were calculated with the BioGrace model using New EC input data. The origincal (default) values in New EC are of 38.40 g CO_2eq/MJ HVO/HEFA (with CH_4 capture) and of 56.50 g CO_2eq/MJ HVO/HEFA (without CH_4 capture). Finally, the VSB model is the only one to consider palm production in Brazil. Despite not considering overseas transportation of palm oil, emissions related to transportation steps are relatively high in view of the distance (2,000 km) covered by trucks.

As in the case of FAME from palm oil, HVO/HEFA from palm oil presents high variation in emissions per MJ of biofuel produced.

9.2.3.2. Cradle-to-pump

In the cradle-to-pump approach, emissions from HVO/HEFA production include the ones reported previously in cradle-to-gate approach, plus emissions from fuel storage and distribution:

- Cultivation of palm (Figure 16);
- Palm transportation to the extraction plant;
- Extraction process;
- Palm oil transportation to the transesterification plant (presented together with palm transportation);
- Hydrogenation process;
- Emissions displaced by co-products;
- HVO/HEFA storage and distribution.

Emissions are presented in g of CO_2eq per MJ of FAME (Table 37 and Figure 20), according to the allocation method of each model, or substitution method as in GHGenius.

Table 37: Cradle-to-pump emissions associated with palm HVO/HEFA production in g CO_2eq/MJ HVO/HEFA, by step of production

	BioGrace		GHGenius	GREET	New EC		VSB
	No cpt	Cpt			No cpt	Cpt	
Cultivation of FFB	14.64	14.64	85.77	11.59	24.24	24.24	18.35
Extraction	29.92	0.00	28.33	1.29	19.73	3.27	1.84
Hydrogenation	9.34	9.34	16.83	20.51	5.79	5.79	2.69
Transportation (palm and oil)	3.85	3.85	3.99	3.67	4.93	4.93	8.06
Emissions displaced by co-products	-	-	-36.89	-	-	-	-
HVO/HEFA distribution and storage	1.15	1.15	1.03	0.45	1.30	1.40	0.63
Total	58.90	28.97	99.06	37.51	55.99	39.63	31.57

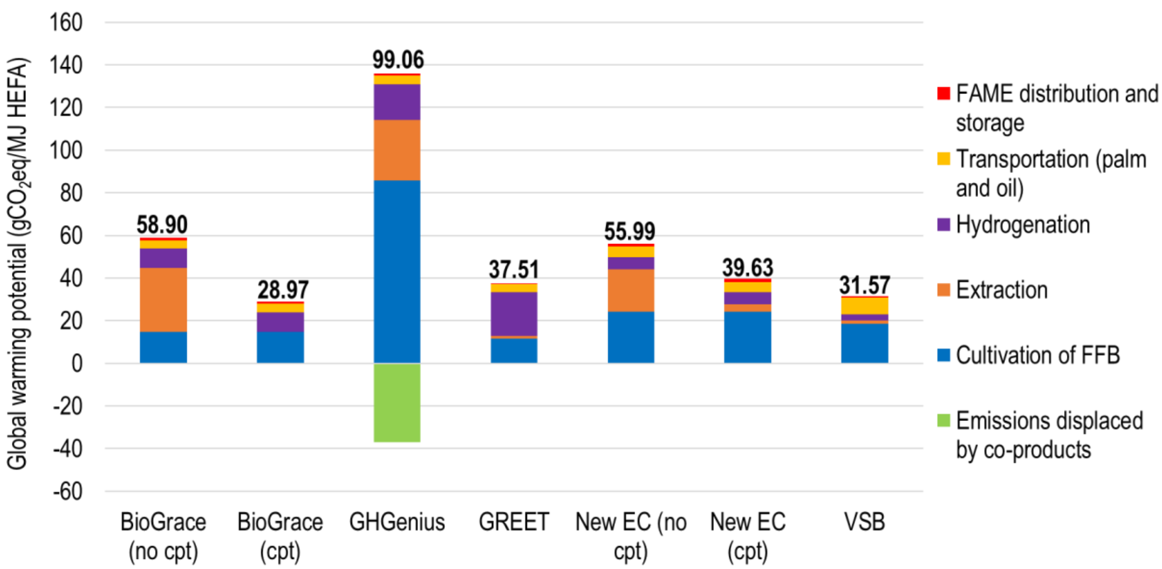

Figure 20: Cradle-to-pump emissions of palm HVO/HEFA production

BioGrace, GHGenius and New EC are similar in the distribution process, while the logistics in the GREET model are similar to those in VSB.

Final remarks for palm HVO/HEFA

Table 38 presents the final remarks concerning palm HVO/HEFA production.

Table 38: Final remarks of model analysis for palm HVO/HEFA production

	BioGrace	GHGenius	GREET	New EC	VSB
Cultivation of palm FFB	Considers EFB compost from palm oil for palm FFB production	High emissions from land use change	Low emissions, low requirement of inputs	High amount of N_2O emissions	High amount of “other field emissions”
Industrial phase	Model is able to consider CH_4 capture. Considers oil refining.	High emissions associated with industrial phase. High consumption of fossil fuels and inputs	High emissions associated with industrial phase. High consumption of fossil fuels and inputs	Model is able to consider CH_4 capture. Considers oil refining.	Low consumption of fossil fuel
Transportation (palm FFB and oil)	Intermediate emissions	Intermediate emissions	Low emissions	Intermediate emissions	High emissions due to large distances and use of truck modal
Distribution	High emissions associated with distribution	High emissions associated with vehicle operation	Low emissions	High emissions associated with distribution	Low emissions
Global warming potential	High emissions, if CH_4 capture from POME is not considered	High emissions due to high amount of LUC emissions, but credits from co-products are not so large as for soybean	Low emissions	High emissions, if CH_4 capture from POME is not considered	Low fossil fuel energy consumption

9.3. Biofuels from used cooking oil (UCO)

The main objective of this section is to present a comparison between the emissions of the pre-existing scenarios of UCO biofuels production (FAME and HVO/HEFA) in four LCA models (excluding GREET, which does not present UCO as a default feedstock) and identification of the particularities leading to different outcomes.

9.3.1. UCO FAME emissions

9.3.1.1. Cradle-to-gate

In the cradle-to-gate approach, emissions from FAME production include:

- Collection/transportation of UCO to the transesterification plant;
- Transesterification process (and pre-processing pathways if considered);
- Emissions displaced by co-products.

Emissions are presented in g of CO_2eq per MJ of FAME (Table 39 and Figure

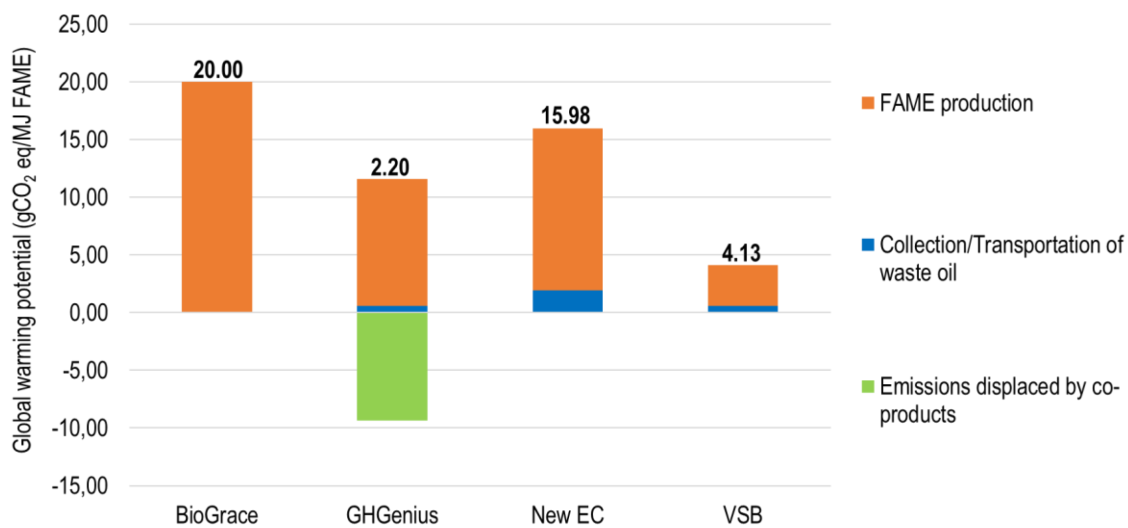

Figure 21), according to the allocation method of each model, or substitution method as in GHGenius.

Table 39: Cradle-to-gate emissions associated with UCO FAME production in g CO_2eq/MJ FAME, by step of production

	BioGrace	GHGenius	New EC	VSB
Collection/transportation of waste oil	-	0.57	1.90	0.57
FAME production	20.01	11.02	14.08	3.56
Emissions displaced by co-products	-	-9.38*	-	-
Total	**20.00**	**2.20**	**15.98**	**4.13**

*related to glycerin

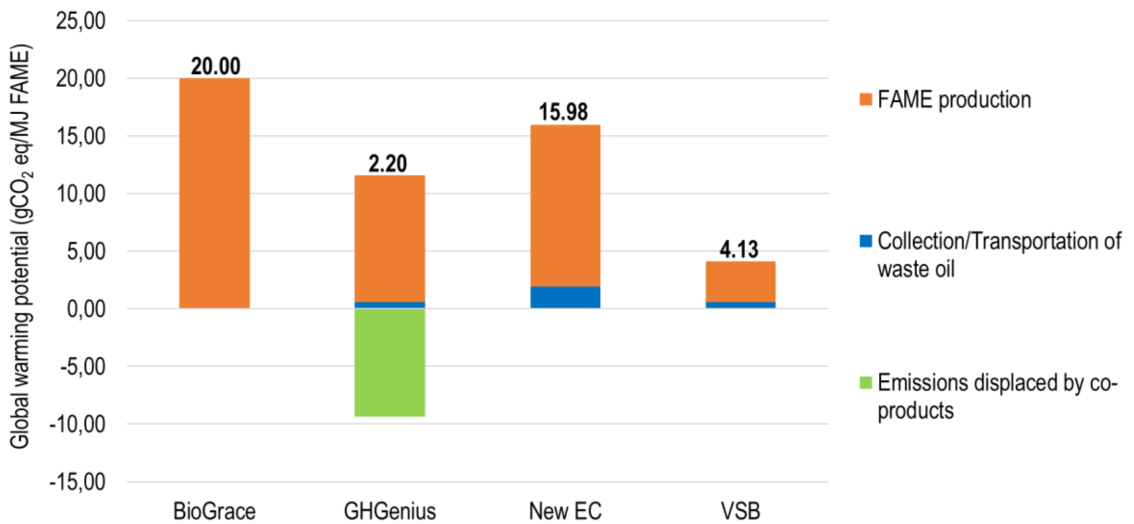

Figure 21: Cradle-to-gate emissions of UCO FAME production

The BioGrace model does not consider any emissions in the collection/transportation phase, but the final FAME emissions are relatively high compared to the other models. Differently from the other models, GHGenius does not allocate emissions, but rather considers co-products credits (substitution procedure for glycerin), which ultimately decreases overall emissions; for instance, BioGrace and New EC consider energy allocation and VSB economic allocation. In New EC, collection/transportation of waste oil presents high emissions compared to the other models, mostly due to UCO coming partly from overseas. Finally, the low fossil fuel consumption in VSB leads to low emissions associated with FAME production. In general, emissions per MJ of FAME from UCO vary among the five models.

9.3.1.2. Cradle-to-pump

In the cradle-to-pump approach, emissions from FAME production include the ones reported previously in cradle-to-gate approach, plus emissions from fuel storage and distribution:

- Collection/transportation of UCO to the transesterification plant;
- Transesterification process (and pre-processing pathways if considered);
- Emissions displaced by co-products;
- FAME storage and distribution.

Emissions are presented in g of CO_2eq per MJ of FAME (Table 40 and Figure 22), according to the allocation method of each model, or substitution method as in GHGenius.

Table 40: Cradle-to-pump emissions associated with UCO FAME production in g CO_2eq/MJ FAME, by step of production

	BioGrace	**GHGenius**	**New EC**	**VSB**
Collection/transportation of waste oil	-	0.57	1.90	0.57
FAME production	20.01	11.02	14.08	3.56
Emissions displaced by co-products	-	-9.38	-	-
FAME distribution and storage	1.26	0.79	1.30	0.73
Total	**21.27**	**2.99**	**17.28**	**4.86**

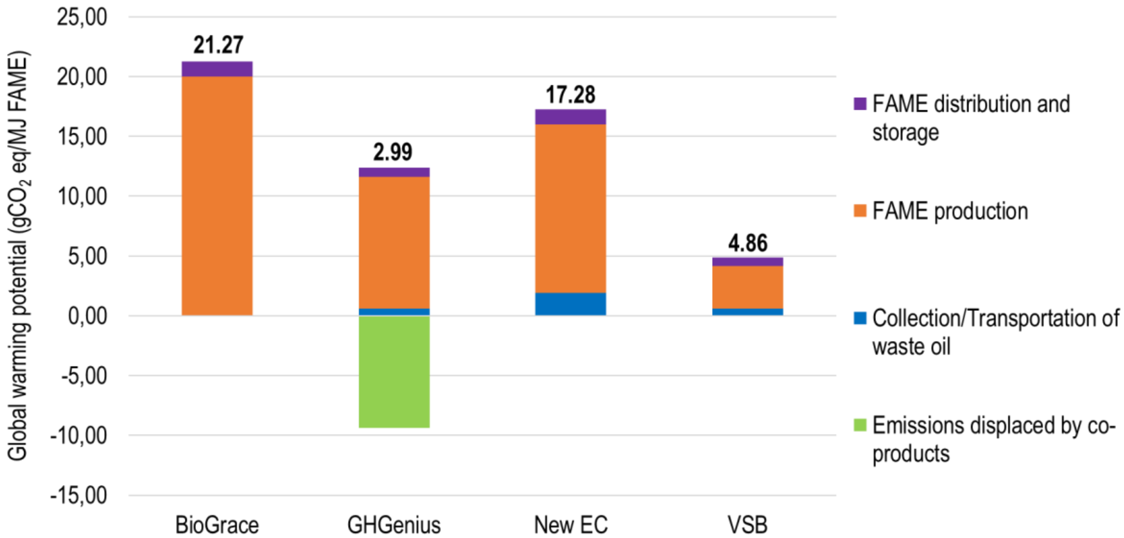

Figure 22: Cradle-to-pump emissions for UCO FAME production

The emission from storage and distribution of UCO FAME are very similar in pairs BioGrace/New EC and GHGenius/VSB. The differences are mostly due to distances and transportation efficiencies in this step.

Final remarks for UCO FAME

Table *41* summarizes the main points with the overall findings in this pathway.

Table 41: Final remarks of model analysis for UCO FAME production

	BioGrace	GHGenius	New EC	VSB
Collection/ transportation of UCO	Does not consider collection/transportation of feedstock	Low emissions. Very close to those in the VSB model	High emissions	Low emissions
Industrial phase	High consumption of fossil energy, H_3PO_4 and methanol. High emission factor for H_3PO_4 and methanol.	Considers an intermediate "upgrading" phase	High fossil energy consumption	Low fossil fuel consumption
FAME distribution	High emissions associated with distribution	High emissions associated with distribution	High emissions associated with distribution	Low emissions
Global warming potential	High emissions	Low emissions due to co-products credits	High emissions	Low emissions due to low fossil fuel consumption. Forest resources and Brazilian electricity have low emission factors.

9.3.2. UCO HVO/HEFA emissions

The results for HVO/HEFA emissions from UCO are presented similarly to UCO FAME emissions.

9.3.2.1. Cradle-to-gate

In the cradle-to-gate approach, emissions from HVO/HEFA production include:

- Collection/transportation of UCO to the transesterification plant;
- Transesterification process (and pre-processing pathways if considered);
- Emissions displaced by co-products.

Emissions are presented in g of CO_2eq per MJ of HVO/HEFA (Table 42 and Figure 23), according to the allocation method of each model, or substitution method as in GHGenius.

Table 42: Cradle-to-gate emissions associated with UCO HVO/HEFA production in g CO_2eq/MJ HVO/HEFA, by step of production

	BioGrace	GHGenius	New EC	VSB
Collection/transportation of waste oil	-	0.77	1.95	0.61
Hydrogenation	10.49	19.08	7.46	2.92
Emissions displaced by co-products	-	-35.72	-	-
Total	10.49	-15.88*	9.41	3.52

*other gaseous: -23.67 and other liquids: -12.05

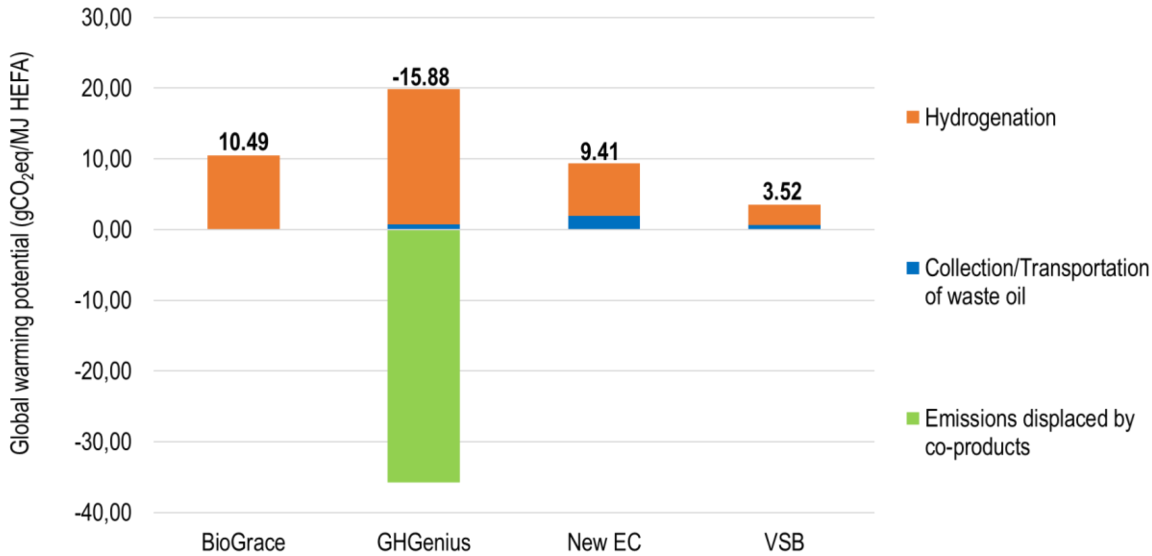

Figure 23: Cradle-to-gate emissions of UCO HVO/HEFA production

As in the other pathways from BioGrace, the model considers a 1.4 factor for converting input values from typical to default in industrial processes (oil extraction and oil transesterification). In the case of HVO/HEFA production, BioGrace presents less energy inputs, consequently, the emissions are similar to New EC. This model also does not consider energy consumption for UCO collection or transportation (UCO enters the industrial process with zero emission) and the allocation procedure is energetic. The substitution procedure in GHGenius accounts for high carbon credits inherent to the model, which leads to negative emissions per MJ of HVO/HEFA produced from UCO. For New EC model, the determined value of 9.41 g CO_2eq/MJ HVO/HEFA was calculated with the BioGrace model using New EC input data, equal to New EC original value: 9.40 g CO_2eq/MJ HVO/HEFA. As in UCO FAME, New EC collection/transportation process is the most energy intensive among the models and it considers energy allocation. Finally, in VSB, the low fossil fuel inputs lead to low emissions associated with hydrogenation process. This model considers economic allocation.

9.3.2.2. Cradle-to-pump

In cradle-to-pump boundaries, emissions from HVO/HEFA production include those previously reported in the cradle-to-gate approach, plus emissions from fuel storage and distribution:

- Collection/transportation of UCO to the transesterification plant;
- Transesterification process (and pre-processing pathways if considered);
- Emissions displaced by co-products;
- FAME storage and distribution.

Emissions are presented in g of CO_2eq per MJ of HVO/HEFA (Table 43 and Figure 24), according to the allocation method of each model, or substitution method as in GHGenius.

Table 43: Cradle-to-pump emissions associated with UCO HVO/HEFA production, in g CO_2eq/MJ HVO/HEFA, by step of production

	BioGrace	**GHGenius**	**New EC**	**VSB**
Collection/transportation of waste oil	-	0.77	1.95	0.61
Hydrogenation	10.49	19.08	7.46	2.92
Emissions displaced by co-products	-	-35.72	-	-
HVO/HEFA distribution and storage	1.15	1.03	1.30	0.63
Total	11.64	-14.85	10.71	4.15

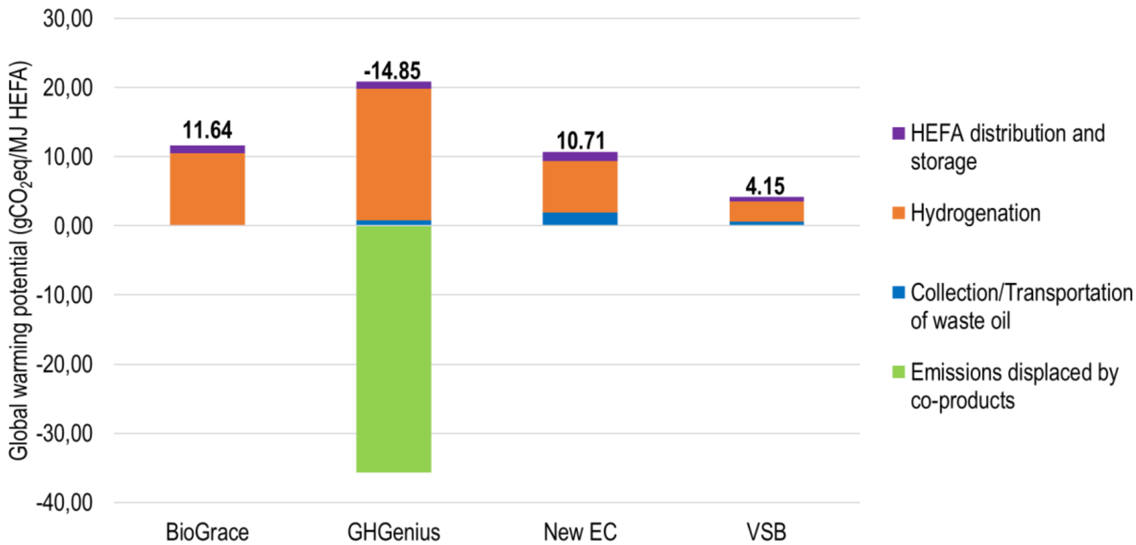

Figure 24: Cradle-to-pump emissions of UCO HVO/HEFA production

Final remarks for UCO HVO/HEFA

Table *44* presents summarized points for the findings of the UCO HVO/HEFA pathway.

Table 44: Final remarks of model analysis for UCO HVO/HEFA production

	BioGrace	**GHGenius**	**New EC**	**VSB**
Collection/ transportation of UCO	Does not consider collection/transportation of feedstock	Low emissions. Very close to those in the VSB model	High emissions	Low emissions
Industrial phase	High fossil energy consumption, H_3PO_4 and methanol. High emission factor for H_3PO_4 and methanol.	Considers an intermediate "upgrading" phase	Does not consider external H_2 input (natural gas is purchased for steam reforming)	Low fossil fuel consumption. High H_2 input.
FAME distribution	High emissions associated with distribution	High emissions associated with vehicle operation	High emissions associated with distribution	Low emissions
Global warming potential	High emissions	Negative emissions due to co-products credits	High emissions	Low emissions due to low fossil fuel consumption. Forest resources and Brazilian electricity have low emission factors.

10. Harmonization of soybean FAME production

This section presents the results obtained after harmonization of soybean FAME production using the VSB dataset and other parameters. The VSB database was used as the basis for the harmonization study in view of the familiarity of the technical team with the model. This was carried out only once since performing multiple harmonization procedures using datasets from different models would ultimately be redundant, as the outcomes would be similar. The only feedstock/pathway duo harmonized was that of soybean FAME due to the worldwide significance of this conversion route for the production of biodiesel.

For the harmonization of soybean FAME production among the studied models, the following procedure was carried out:

- Retrieval of information from the VSB database:
    - Inputs: all inputs amounts have been harmonized since they describe the production system.
    - Emission factors: the harmonized factors are those identified as the ones with the highest influence on the final results and the most discrepant ones among all models (mainly mineral fertilizers, diesel, and methanol).
- Insertion of the retrieved information in each of the remaining models (except for New EC) in a step by step basis to identify changes in emissions along the FAME production chain.

In the harmonization procedure, the emission factors associated to methanol were also harmonized since this could lead to discrepant results in the analysis. The oxidation of fossil C in methanol was only included in the biodiesel emissions (FAME use phase). For instance, BioGrace considers the emissions associated to the oxidation of fossil C in methanol in its default values. In this case, such emissions are allocated among the co-products of the transesterification step. Figure 25 presents the results for the harmonization of soybean FAME production using VSB data, i.e. considering the Brazilian soybean production system and industrial oil extraction/conversion using Brazilian data. It is important to highlight that the New EC was not included in the harmonization procedure: despite the data for several scenarios being available online (and an external user would be able to "rebuild" the calculation structure, if needed), the spreadsheet with the calculation tool is locked for edition by users. This led to the removal of New EC from this specific section of the study since the purpose of a harmonization exercise is not only identifying the differences between assumptions and input data from each model, but also understanding the underlying features of the calculation mechanism itself.

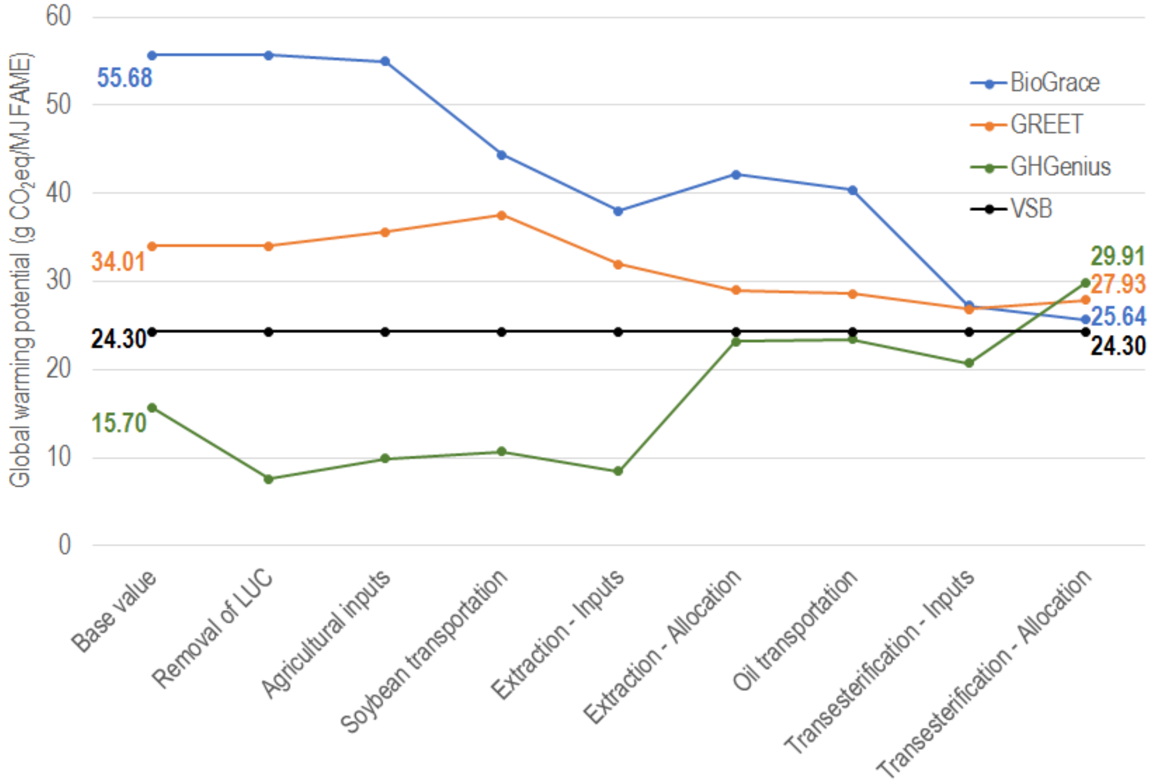

Figure 25: Harmonization of soybean FAME production emissions

Figure 25: Harmonization of soybean FAME production emissionsclearly indicates that the differences among the four assessed models decrease considerably and they all reach similar results after harmonization of a few chosen inputs and parameters.

The harmonization of soybean transportation, extraction inputs and finally transesterification inputs contributed significantly to approximate BioGrace to VSB. For GHGenius, it was the change of substitution procedure to economic allocation of soybean meal that considerably approximated the model to VSB results; however, after the harmonization of transesterification inputs and allocation method, the differences between these two models increased again. In general, for GREET, each harmonization step led to similar final results, but the most pronounced change was the harmonization of extraction inputs that contributed to approximate the GREET estimate to that of VSB.

The remaining small differences among the results are due to some unharmonized points:

- BioGrace: the default emission factor for methanol includes burning (this is usually only considered in the use phase of the lifecycle analysis).
- GHGenius: the model calculates low emissions for the industrial phase and higher emissions for transportation in comparison with other models.
- GREET: the model presents several differences along the production chain that ultimately accumulate and affect the result, such as transportation efficiencies and emission factors of minor inputs.
- VSB: in an overall analysis, it preferentially considers energy sources with low emissions (such as forest resources) to power industrial processes.

Additionally, another point affecting the harmonization procedure is the set of characterization factors considered by each model, as presented in Table *45*: Default characterization factors considered by each modelTable 45. GHGenius also takes into account several characterization factors to convert several other compounds (such as VOC, NOx, fluorides, etc.) into CO_2eq using 2007 IPCC GWP data. The characterization factors of the New EC model, although not included in the harmonization study, are shown here.

Table 45: Default characterization factors considered by each model

	BioGrace	**GREET**	**GHGenius**	**New EC**	**VSB**
CO_2	1	1	1	1	1
CH_4	23	30	25	25	25
N_2O	296	265	298	298	298

Differences are expected among the models since each one considers feedstock production with different production systems, transportation methods and industrial conversion. The objective of the harmonization was to show that the models are able to achieve similar carbon intensities for soybean FAME after standardization of the main differences.

11. Conclusions and final remarks

The study presented in this report was able to quantitatively identify the factors contributing to differences in the results in five different LCA models and the main parameters impacting the determination of the emissions associated to the production and use of FAME and HVO/HEFA from different feedstocks. Table 46 summarizes the default results for each assessed feedstock/pathway duo using the studied LCA models.

Table 46: Summary of cradle-to-pump emissions in g CO_2eq/MJ biofuel

	BioGrace	GHGenius	GREET	New EC	VSB	Δ GHG emissions[1]
Soybean FAME	**56.94**	**16.90**	34.47	42.27	25.03	***40.04***
Soybean HVO/HEFA	**50.63**	48.58	47.57	41.94	**25.46**	***25.17***
Palm FAME[2]	65.96	**78.21**	**24.15**	57.97	30.78	***54.06***
Palm FAME[3]	**36.94**	**-**	**-**	**42.23**	-	***5.29***
Palm HVO/HEFA[2]	58.90	**99.06**	37.54	55.99	**31.57**	***67.49***
Palm HVO/HEFA[3]	**28.97**	**-**	-	**39.63**	**-**	***10.66***
UCO FAME	**21.27**	**2.99**	-	17.28	4.86	***18.28***
UCO HVO/HEFA	**11.64**	**-14.85**	-	10.71	4.15	***26.49***

Red cells represent the highest emissions among models, while green cells indicate the lowest ones
[1] Difference between the highest and lowest emission
[2] Does not include CH_4 capture from palm oil mill effluent (POME)
[3] Include CH_4 capture from palm oil mill effluent (POME)

BioGrace estimates the highest emissions in soybean and UCO pathways. GHGenius also estimates the lowest GHG emissions for three pathways: UCO biofuels and soybean FAME. VSB follows with HVO/HEFA from soybean and palm and GREET has the lowest emissions only for palm FAME. Palm biofuels can also be assessed in two variants: with or without the capture of CH_4 from palm oil mill effluent. This option is only taken into account by

BioGrace and New EC, both of which clearly demonstrate the impact in carrying out this additional operation associated to palm oil extraction.

Besides, the harmonization procedure carried for the soybean FAME pathway shows it is possible to align the results issued by the models through a series of steps considering only few parameters. The analysis found differences in the input data and methodological choices, some of which could be harmonized, such as the divergences between soybean cultivation system among the studied models.

The industrial phase of each pathway, however, should have similar results in the assessed models since the industrial conversion of oils is not supposed to significantly vary for the production of a given biofuel. This conclusion could specifically exclude the VSB, which considers renewable sources of energy for powering oil conversion. This is further supported by the results obtained for both FAME and HVO/HEFA from UCO: the industrial conversion should not present discrepant results, since this feedstock lacks an input-intensive agricultural production step such as that for soybean and palm.

In this sense, there is room for discussion and standardization of models in order to decrease the variance of input data and approaches (e.g. necessity of a collection phase for UCO) and thus "pre-harmonize" all models and make them more consistent.

Additional reliable empirical data indicating whether one value is more accurate than another may be required to justify the harmonization of parametric assumptions across models. However, even then there may be regional- or scenario-specific differences that justifiably lead to different parametric values. An effort to build a harmonized dataset of input data for the technological pathways and to update the databases of the main models would benefit the community and deliver better GHG emission results for the life cycle assessment of biofuels.

In the sequence of this study, a similar approach will be employed for the assessment of 2G ethanol from multiple feedstocks (namely sugarcane lignocellulosic material - bagasse and straw, corn stover, wheat straw and forest residues). In this way, along with the results from Phase 1 and those presented in this Report, several pathways for the production of the two most common biofuel types (ethanol and biodiesel) will be covered in this IEA Bioenergy Task 39 study.

Acknowledgments

The authors of this Technical Report would like to thank the comments and suggestions made by IEA Bioenergy Task 39 Steering Committee that helped in improving the final quality of the document: Michael Wang (Argonne National Laboratory, USA), Don O'Connor ((S&T)^2 Consultants Inc., Canada), Mark Staples (Massachusetts Institute of Technology, USA), and Adrian O'Connell and Laura Lonza (EC Joint Research Center, EU). The authors also thank Franziska Müller-Langer, Timo Gerlagh, John Neeft, Dina Bacovsky, and Luc Pelkmans, members of IEA Bioenergy Task 39, for enriching the discussion of this report.

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