Comparison of greenhouse gas accounting principles between the US and the EU

Towards harmonizing geographical approaches for GHG fuel emission factors

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Disclaimer

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About Smart Freight Centre

Smart Freight Centre is an international non-profit organization focused on reducing greenhouse gas emissions from freight transportation. Smart Freight Centre's vision is an efficient and zero emission global logistics sector. Smart Freight Centre's mission is to collaborate with the organization's global partners to quantify impacts, identify solutions, and propagate logistics decarbonization strategies. Smart Freight Centre's goal is to guide the global logistics industry in tracking and reducing the industry's greenhouse gas emissions by one billion tonnes by 2030 and to reach zero emissions by 2050 or earlier, consistent with a 1.5°C future.

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Executive Summary

Low-carbon and sustainable biofuels can play a short term role in decarbonizing the road freight sector, where zero emission technology is not yet readily available. It can act as a short term drop-in fuel to electric and fuel cell vehicles, especially as these technologies and markets continue to mature. However, understanding the extent to which these biofuels can reduce GHG emissions on a lifecycle basis is a challenge due to the wide variety of feedstock supply chains and use cases, as well as different methodologies for emission accounting in the biofuel production sector.

Due to the complexity of biofuel greenhouse gas lifecycle assessment, it is vital to provide transparency into the process of incorporating emission factors from any existing database into the set of default factors provided in the Global Logistics Emission Council (GLEC) Framework. This ensures that the necessary steps towards harmonization of emission factor assumptions are taken, providing a consistent approach across different emission database sources and geographical regions.

The Comparison of greenhouse gas accounting principles between the US and the EU report is part of Smart Freight Centre's series on low and zero emission fuels, where we address different perspectives on impact, emissions and implementation challenges of biofuels as a decarbonization solution. The full series is available here.

This report analyzes the development of US biofuel emission factors in the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model developed by Argonne National Laboratory with the following aims:

- Provide visibility into the development of emission factors in the GREET 1 database, which focuses on the fuel lifecycle analysis, specifically in terms of database structure, emission categories, and calculation approach.
- Provide recommendations on emission factor values to be used for North American biofuels in the GLEC Framework
- Provide recommendations for harmonization of US and Europe emission factor calculation approaches and accounting principles, in terms of feedstocks, production pathways, emission categories, and separate categories for emissions from land-use change and indirect land-use change.

For comparison, the EU emission factor sources are taken from Annex V of the Renewable Energy Directive II (RED II) and the JEC Well-to-Wheels report v5 (JECv5). Both sources have been used to define the biofuel emission factors used in GLEC Framework, and have been analyzed in Smart Freight Centre's Desktop Review of GHG Emission Factors for Road Freight and ifeu work on the EcoTransIT World-Environmental Methodology and Data report referenced in ISO 14083.

The fuels studied are petroleum-, natural gas-derived fuels, and their biofuel replacements:

- Gasoline
- Diesel
- Liquefied natural gas (LNG)
- Bioethanol
- Biodiesel
- Renewable diesel
- Liquefied biomethane (LBM)

Database structure

The GREET model includes more than 100 fuel production pathways/energy systems from various energy feedstock sources, though not all at the same level of detail and some have been updated more recently than others. The most important biofuel production pathways are:

- Ethanol produced from food crops, such as corn, corn stover, and sugarcane.
- Biodiesel produced from oilseed crops, such as soybean and rapeseed, as well as from waste-based feedstock, such as used (waste) cooking oil, distillers corn oil, and animal fats.
- Renewable diesel (HVO in Europe) produced from oilseed crops, such as soybean and rapeseed, as well as waste feedstock such as animal fats.
- Liquefied biomethane.

As such, there is significant coverage of different types of fuels between GREET 1 and the biofuel production pathways covered in the JEC WTW v5 and RED II. The key difference is that GREET predominantly includes the production of renewable diesel also known as HVO in Europe, via other processes besides hydrogenation, such as gasification, pyrolysis and other biochemical and thermochemical technologies. RED II partly covers other processes for renewable diesel excluding HVO. Another key difference is that the emission factor of waste-derived renewable natural gas in GREET is much lower than their European counterparts due to high emission credits from avoided emissions.

Emission categories

The GREET model includes a module for estimating land use and land management change emissions using the Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB) and the Global Trade Analysis Project (GTAP). According to RED II, direct land use change emissions are to be included in the emission factor calculation, but in Europe it does not occur anymore since it is not feasible to convert land to land for biofuel production as this would lead to GHG emissions above the threshold set in RED II. Indirect land use change (iLUC) emissions are not included in RED II GHG values because of the high uncertainty in the values provided, however, RED II is limiting the use of biofuels with a high risk of iLUC (e.g. palm oil) and looking to phase out these feedstocks in near future. As an example of comparing iLUC values for biodiesel from soybean, the GREET value is 9 g CO_{2e}/MJ while in the RED II has 55 gCO_{2e}/MJ. This is due to the fact that iLUC can vary considerably across biofuel pathways, mainly contingent on technologies and feedstocks, and iLUC emissions are uncertain and sensitive to modeling parameters and assumptions.

GREET takes into account methane slip for the biomethane emission factor, which is not explicitly addressed in the European databases. Nevertheless, a recent Smart Freight Centre analysis in 'The Potential of Bio-LNG in Decarbonizing Logistics' Whitepaper addressed and estimated the amount of methane slip emissions in liquefied biomethane.

Other challenges that require harmonization include issues surrounding the use of avoided emissions, biogenic and industrial removals, and credit schemes.

Recommendations

The following recommendations for further research will help harmonize the approaches for emission factor development in the Europe and the US.

- Develop common consensus to address the (i) inclusion of methane slip, and (ii) allocation of avoided emissions in GHG accounting principles for the end-users to have a universal accounting and reporting structure.
- Develop principles to take into account when developing emission factors for GHG emission reporting, in particular as emission factors are evolving over time due to the introduction of new energy carriers, the available technology for the production of fuels improves, and lower emission energy sources are deployed to power production processes.
- Review how iLUC emissions can be estimated with greater reliability, such that it can be included in freight emissions reporting and the GLEC Framework emission factors.

Future work will include reviewing the availability of synthetic and e-fuels in the market and importance to be included in the GLEC Framework.

1 Introduction

The Comparison of greenhouse gas accounting principles between the US and the EU report is part of Smart Freight Centre's series on biofuels, where we address different perspectives on impact, emissions and implementation challenges of biofuels as a decarbonization solution. The full series is available here.

A quick transition to low or zero-emission fuels and vehicle technology is essential to meet the goals of the Paris Agreement on climate change in the freight and logistics sector. The road freight sector accounts for over 10% of global greenhouse gas emissions, and these emissions are increasing (E. & I. S. Department for Business, 2022). In the US, 36% of greenhouse gas (GHG) emissions in 2020 came from the transport sector, of which 17% are due to light-duty vehicles and 26 % due to medium- to heavy-duty vehicles. This is largely due to the almost exclusive reliance on petroleum-derived liquid fuels (e.g., gasoline and diesel) as an energy source (Environmental Protection Agency, 2022).

Low-carbon and sustainable biofuels can play a role in decarbonizing the freight sector alongside other technologies, such as electric and fuel cell vehicles, especially as these technologies and markets continue to mature (N. Gray et al., 2021) (R. Chen et al., 2018). However, understanding the extent to which these biofuels can reduce emissions is a challenge with the wide variety of feedstock supply chains and uses, as well as different methodologies for emission accounting in the biofuel production sector.

The Smart Freight Centre supports companies in emission reduction related to their freight transport, through the Global Logistics Emission Council (GLEC) Framework, the industry's standard methodology for tracking freight GHG emissions. Part of the ongoing development work of the GLEC Framework is the identification and review of reliable GHG emission factors from lifecycle emission factor databases established in different transport markets.

1.1 GHG emission factors

A GHG emission factor indicates the mass of carbon dioxide equivalent (CO_{2e}) released for a quantity of fuel or electricity used. The GLEC Framework uses full fuel lifecycle emission factors, i.e., covering emissions produced in both Well-to-Tank (WTT) and Tank-to-Wheel (TTW) phases. WTT emissions consist of emissions during the fuel production and distribution, while the TTW emissions consist of emissions from the combustion of fuel (Smart Freight Centre, 2019). The GLEC Framework provides default emission factors for a wide variety of fuels, which are based on representative and reasonable estimates for a specific area (e.g., the EU or North America). These default emission factors are often used in place of certified emission factors specific to a fuel batch, when they are unavailable, and thus play an important role in emission disclosure practices.

For biofuels, the carbon-based emissions (i.e., carbon dioxide, carbon monoxide and volatile organic compounds) in the TTW phase is designated zero, as it is assumed that an equivalent amount of carbon dioxide is sequestered from the atmosphere as the biomass grew, whether from agriculture or naturally. This means that a major component of the lifecycle emissions comes the WTT phase, that is from the agricultural and industrial activity. Biofuel WTT emissions strongly depend on the type of feedstock used and the production pathways, which in this flourishing sector, keep diversifying. Further, regional practices adopted by emission factor databases may allow for various ways to deal with different emission categories, notably carbon or manure credits, induced or indirect land use change.

Due to the complexity of biofuel greenhouse gas lifecycle assessment, it is vital to provide transparency into the process of incorporating emission factors from any existing database into the set of default factors provided in the Global Logistics Emission Council (GLEC) Framework. This ensures that the necessary steps towards harmonization of emission factor assumptions are taken, providing a consistent approach across different emission database sources and geographical regions.

1.2 Objectives and scope

This report addresses a critical absence in the GLEC Framework, namely North American biofuel emission factors. Specifically, the report will address the following:

- Provide visibility into the development of emission factors in the selected US-based lifecycle emissions factor database, specifically in terms of database structure, emission categories, and calculation approach.
- Provide recommendations on emissions factor values to be used for North American biofuels in the GLEC framework
- Provide recommendations for harmonization of US and Europe emission factor calculation approaches and accounting principles, in terms of feedstocks, production pathways, emission categories, and separate categories for emissions from direct and indirect land-use change.

The study uses the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model, developed by Argonne National Laboratory with funding from the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy [13], which is viewed as the de facto standard when it comes to transport lifecycle emission factors in the US. For comparison, the EU emission factor sources are taken from Annex V of the Renewable Energy Directive (recast) (RED II) and the JEC Well-to-Wheels report v5 (JECv5). Both sources have been used to define the biofuel emission factors used in the GLEC Framework and ifeu work on EcoTransIT World-Environmental Methodology and Data report included in ISO 14083.

The fuels studied are petroleum-, natural gas-derived fuels, and their biofuel replacements:

- Gasoline
- Diesel
- Liquefied natural gas (LNG)
- Bioethanol
- Biodiesel
- Renewable diesel
- Liquefied biomethane (LBM)

1.3 Report structure

The structure of the report is as follows. Section 2 presents the analysis of the GREET model structure. Section 3 presents the analysis of methodology resulting in a list of adaptations needed to be harmonized with the GLEC Framework. Section 4 presents the results of adapting the GREET model emission factors for biofuels and comparing it with the European values. This section also presents insights into the differences between the values of fuels used in the US and the EU. Section 5 concludes with highlighting several steps to take to increase harmonization of emission factor work for biofuels and emerging fuel types.

2 Analysis of the GREET model structure

This section presents an overview of the GREET model by way of clarifying the tool's general structures, the units used and vehicle types, as well as its scope, with respect to biofuel production pathways, emission categories, emissions from land-use and land management change, indirect land use change (iLUC) and methane slip.

2.1 Overview of the GREET tool

The GREET model (H. Kwon and U. Lee, 2019) is an analytical tool and hybrid model that simulates the energy use and emission output of various vehicle and fuel combinations. The GREET model is utilized by more than 45,000 users around the world including government agencies, national labs, universities and industry. It is also an integral part of transportation and bioenergy technology evaluation. GREET plays a valuable role in the identification of opportunities for improving the sustainability of technologies, promoting the clean and efficient vehicle and fuel technologies, and informing policies through high-quality, consistent and peer-reviewed analyses and publications.

In GREET, the process is primarily based on the attributional lifecycle assessment (LCA) approach, while land-use change is essentially based on the consequential approach. GREET includes all transport subsectors such as road, air, rail and marine and in the current version of 2021 also includes LCA of buildings and building technologies. GREET can be accessed using two platforms: the GREET Excel model and the GREET.net model.

GREET Excel provides a comprehensive lifecycle-based approach to comparing the energy use and emissions of conventional and advanced vehicle technologies. It consists of two separate excel sheets:

- GREET 1 presents the lifecycle analysis of the transport fuel, encompassing the fuel cycle, that is the well-to-tank and tank-to-wheel emissions.
- GREET 2 presents the lifecycle analysis of the vehicle and provides energy and emission effects associated with vehicle material recovery and production, vehicle component fabrication, vehicle assembly, and vehicle disposal or recycling.

GREET.net provides a more user-friendly graphical interface to perform lifecycle analysis simulations of alternative transportation fuels and vehicle technologies and makes use GREET1 and GREET2 Excel models.

2.2 Units used as inputs and outputs

The GREET model has various functional units depending on the services (e.g. mile, tonne-mile, tonne-km, passenger-mile), outputs (e.g. MMBtu, MJ, gasoline gallon equivalent), and resources (e.g. per tonne of biomass) (Argonne National Laboratory, 2021) (ibid). The interface allows the user to quickly convert the units from one to another.

The values reported in this report are based on SI units (i.e. g CO_{2eq}/MJ).

2.3 Vehicle type

GREET includes more than 80 on-road powertrain/fuel systems for both light-duty and heavy-duty vehicles (M. Wang, 2021). Table 1 provides an overview of the engine type and respective fuel use in the GREET model. The fuel reported is based on the utilization in the class 7/8 trucks i.e., heavy-duty vehicles that are mostly used for road freight in the U.S.

Table 1 Overview of vehicle engine type and fuels used (H. Kwon and U. Lee, 2019) (A. Elgowainy, 2019)

Engine Type	Fuel used
Conventional spark-ignition engine vehicles	Gasoline
	CNG, LNG and LPG
	Gaseous and Liquid Hydrogen
	Renewable gas
	Methanol and Ethanol
Spark ignition, direct-Injection Engine Vehicles`	Gasoline
	Methanol and ethanol
Compressed-ignition, direct-injection engine vehicles	Diesel
	Fischer-Tropsch Diesel
	Dimethyl Ether
	Biodiesel
	Renewable diesel
Fuel cell vehicles	On-board hydrogen storage- Gaseous and liquid hydrogen from various sources
	On-board hydrocarbon reforming to hydrogen
Battery powered electric vehicles	Various electricity generation sources
Hybrid electric vehicles (HEVs)	Spark-ignition engines Gasoline Renewable Gas CNG, LNG and LPG Gaseous and liquid Hydrogen Methanol and ethanol
	Compressed-ignition engines Diesel Fischer-Tropsch Diesel Dimethyl ether Biodiesel Renewable diesel
Plug-in hybrid electric vehicles	Spark-ignition engines Gasoline CNG, LNG and LPG Various electricity generation sources Gaseous and liquid Hydrogen Methanol and ethanol
	Compressed-ignition engines Diesel Fischer-Tropsch Diesel Dimethyl ether Biodiesel Renewable diesel

2.4 Fuel production pathways

The GREET model includes more than 100 fuel production pathways/energy systems from various energy feedstock sources (Figure 1), though not all at the same level of detail and some have been updated more recently than others.

These include:

- conventional fuels derived from fossil fuels, such as petroleum and natural gas,
- hydrogen produced from fossil fuels, biomass, electricity and nuclear energy, as well as including carbon capture system
- electricity produced from fossil fuels, biomass, renewable power plants and nuclear energy, as well as including CCS
- biofuels
- e-fuels produced from renewable hydrogen and CO_2 sources.

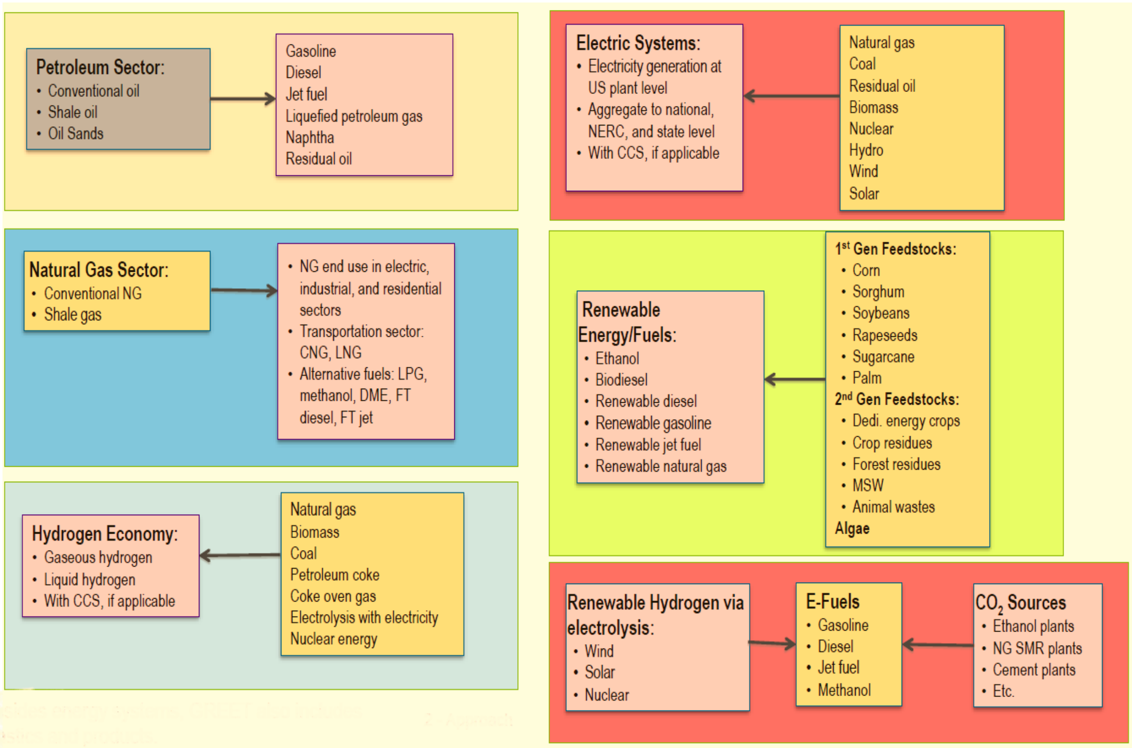

Figure 1 Fuel production pathways included in the GREET mode (adapted) (M. Wang, 2021)

GREET includes various possible feedstocks and conversion technologies for production of biofuels as depicted in Figure 2. These production methods are described extensively in the GREET model.

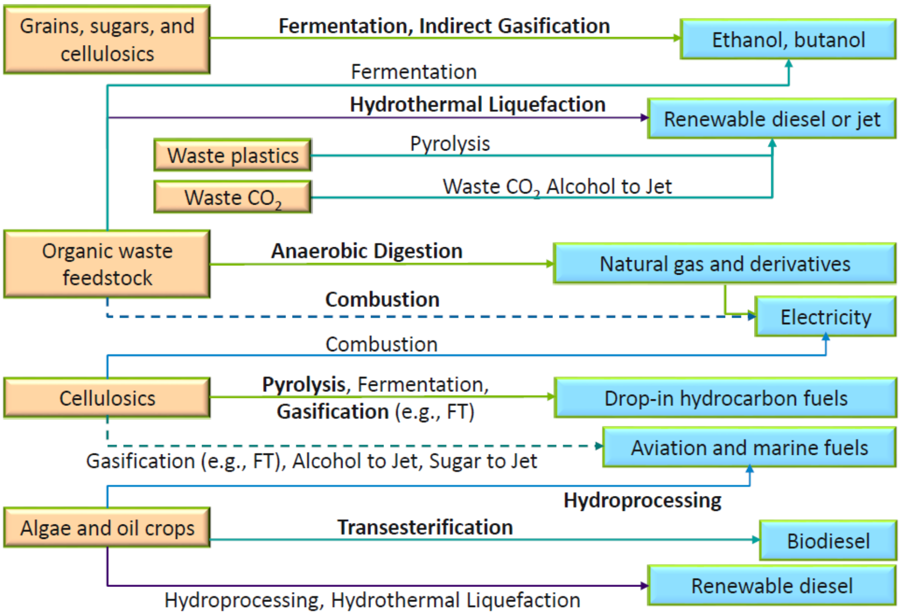

Figure 2 Detailed production pathways of biofuels in the GREET model (adapted) (H. Kwon and U. Lee, 2019)

For the purpose of this report, i.e., for potential inclusion in the GLEC Framework, only major production pathways are analyzed. These are based on feedstocks that are prominent in the US market, as well as those which fall under the Low Carbon Fuel Standard (LCFS) and the Renewable Fuel Standard (RFS).

- Ethanol produced from food crops, such as corn, corn stover, and sugarcane.
- Biodiesel produced from oilseed crops, such as soybean and rapeseed, as well from waste-based feedstock, such as waste cooking oil, corn oil, and animal fats.
- Renewable diesel produced from oilseed crops, such as soybean and rapeseed, as well as waste feedstock i.e., animal fats.
- Liquefied biomethane produced from landfill gas and wet manure.

2.5 Energy and Environmental Metrics

The model sustainability metric includes energy use (fossil and renewable), and air pollutants (such as VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, BC, OC, and SO_x) which are estimated separately for total and urban, greenhouse gases (CO_2, CH_4 and N_2O) combined with their global warming potentials, and water consumption (Argonne National Laboratory, 2021) (ibid). Land-use change and indirect land-use change along with methane leakage is also addressed as it is mostly associated with the storage and transportation of volatile fuels.

Land-use change and land management change

Direct land-use change refers to a process in which human activities transform the natural landscape for economic activities e.g., from forest to farmland to produce crops for biofuels. Human activities which affect terrestrial sinks with land use, land-use change and forestry (LULUCF) activities, alter the exchange of CO_2 (carbon cycle) between the terrestrial biosphere system and the atmosphere (UNFCCC, 2017). The changes in land use, as well as management processes, have a massive impact on the soil ecosystems and in turn, can affect key soil functions (D. J. Spurgeon, 2013).

The Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB) (H. Kwon, 2021) from the GREET model is used for analyzing the GHG emissions from land-use change (LUC) and land management change (LMC) in the biofuel life cycle analysis (LCA). The values are expressed in grams of carbon dioxide equivalent per MJ of fuel produced.

The Global Trade Analysis Project (GTAP) developed by Purdue University is used to estimate the domestic area (US) and international land areas such as forest, grassland, cropland pasture, and feedstock lands that transitions to another land type at the agro-ecological zone(AEZ), which is multiplied by corresponding emission factors (EF) aggregated/disaggregated from different spatial coverages, to estimate LUC GHG emissions for biofuel production scenarios (Figure 3).

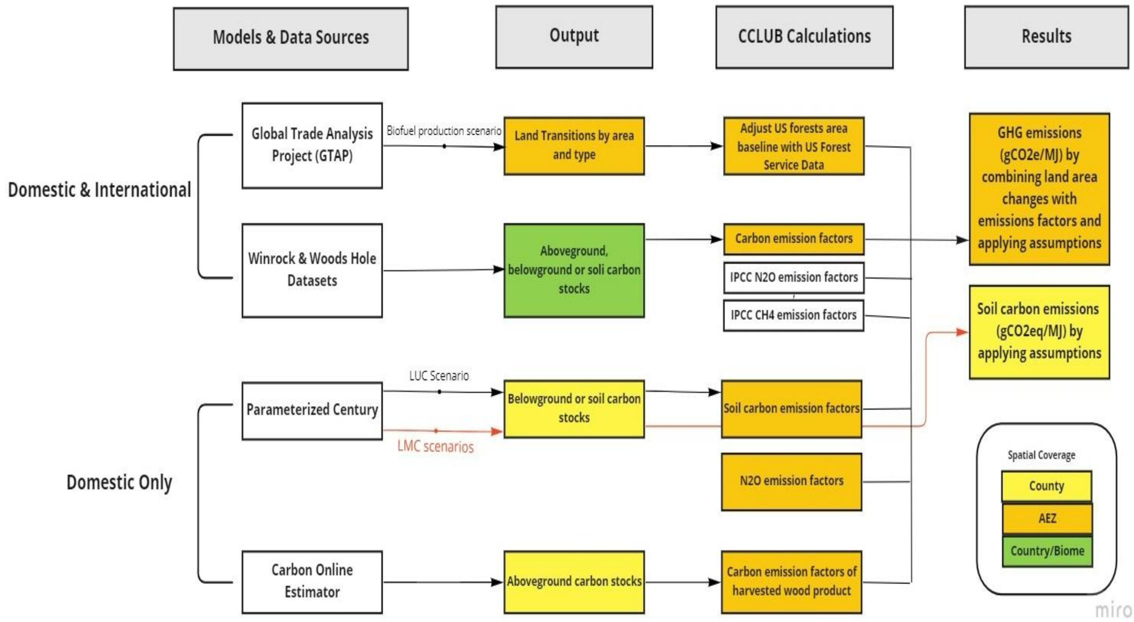

Figure 3 Schematics of land use change in GREET (ibid)

Indirect land-use change

Crop-based biofuel production may cause indirect land-use change (iLUC) emissions (Z. Qin and H. Kwon, 2018). iLUC refers to the indirect carbon emissions that would be expected to occur due to diverting (crop-based) feedstocks from their current use or purpose to the production of biofuels. This relates to the fact that consumption of a feedstock to produce biofuels results in a constraint on the availability of that feedstock for use in other purposes (e.g., food production). This leads to an expansion in its production to meet market needs. Where this increase in production leads to the clearing of and/or cultivation of additional land, this can result in a loss of carbon storage capacity (e.g., due to the felling of the forest) causing additional carbon emissions. These emissions are attributable to the action that caused them (i.e., the production of crop-based biofuels) to provide a complete system picture of the greenhouse gas profile of biofuels produced from different feedstocks.

In the GREET Model, the iLUC emissions are calculated with the use of models that decide the area changes of specific land types and EFs for conversion of one land type to another. The factors responsible for iLUC emission calculations are (ibid):

- the area of land that transits from one type of land use to another; and,
- the EFs that determine specific (i.e., CO_2, N_2O, and CH_4) or total GHG emissions per unit area changed associated with specific iLUC.

When it comes to calculation of indirect land-use change values, it is not easy (essentially impossible) to determine who causes indirect land-use change and to separate it from direct land-use change. Without common standards for the treatment of different land use emission scenarios this leads to wide variability of outputs. For example, in the case of biodiesel soybean, the iLUC value from GREET is 9 g CO_{2e}/MJ whereas from RED II the equivalent value is 55

gCO_{2e}/MJ. Thus, bearing this uncertainty in mind, the addition of the iLUC contribution to the lifecycle emissions has been shown to outweigh the benefits of using some potential biofuel feedstocks, especially soy and palm oil in Europe and the implementation of the RED II directive has restricted the amount of biofuel production from traditional crop-based feedstock to limit the impact of indirect land-use change emissions.

Therefore, to be compatible with the European values and the new ISO 14083, iLUC is not included into the GHG emission factors but given separately.

Methane Slip

Over the years there has been much debate about the potential benefits of gaseous fuels, particularly natural gas, as part of the energy transition to a low-carbon transport sector. The debate arises because methane is both volatile and a strong greenhouse gas, meaning that it does not take much leakage to negate any benefit from the theoretical benefits that might result from full combustion of what is potentially a more energy-efficient fuel.

The scope of this study does not include an in-depth discussion of this issue. Initial comparison of GREET with European databases has concluded that GREET takes methane slip into account, whereas many of the European databases do not, limiting their analysis to an assumption of full combustion. Nevertheless, a recent Smart Freight Centre analysis in ‘The Potential of Bio-LNG in Decarbonizing Logistics’ Whitepaper addressed and estimated the amount of methane slip emissions in liquefied biomethane, and also included in the recent update of the GLEC Framework.

3 Methodology

3.1 Database development

The GREET database builds upon past iterations of its life-cycle inventory datasets and additional data sets that are compiled from industrial surveys, government databases, other national laboratories' databases and literature. For baseline technologies and systems, the values are taken from Energy Information Administration (EIA) data and annual energy outlook projections, for electric systems U.S Environmental Protection Agency (EPA) eGrid, and water US geology services (M. Wang, 2021). The farming data from United States Department of Agriculture (USDA), energy use from ethanol plants, and operational data from oil sands and shale oil are used as underlying data for the field operation (H. Xu et al., 2022) (A. Elgowainy, 2019) (H. Kwon and U. Lee, 2019).

For certain fuel production such as renewable diesel datasets, a simulation model such as the ASPEN plus model is used. As for fuel economy calculations, data is collected from the Argonne National Laboratory (ANL) Autonomie database, whereas the data sets for LUC and iLUC values are taken from the CCLUB model (M. Wang, 2021), (H. Kwon, 2021). In the case of vehicular emission calculation, the values are based on EPA Moves and EPA AMPD (stationary) (M. Wang, 2021). For data for petroleum refinery operations, linear programming models are used, while electricity utility dispatch models are used for marginal electricity analysis (A. Elgowainy, 2019). The inputs from industrial surveys are used for the data collection on fuel producers and technology developers with the automakers and system components producers on vehicles (H. Kwon and U. Lee, 2019) (A. Elgowainy, 2019), (Argonne National Laboratory, 2014).

ANL collected datasets for major biodiesel and renewable diesel pathways through industrial surveys with the support of the National Biodiesel Board (NBB) and the North American Renders Association (NARA) (H. Xu et al., 2022).

3.2 Calculation approach

In GREET, life cycle calculation has several stages such as end-use, transportation, distribution, and production, and each stage is represented as a stationary or transportation process (Argonne National Laboratory, 2014). Within each process step, the emission is emitted through

- combustion of fuels for heat and energy for the process, and
- leakage through the storage and transportation of volatile fuels.

In the result overview, emission factors (EF) are broken down into feedstock, fuels, and vehicle operations.

The flow of the calculation in the GREET model is shown in **Figure** 4: energy input accounting to a process is done based on a list of resources, associated amounts and leakage rates(Argonne National Laboratory, 2021). For process emissions accounting, notion of technology is used, where technology is an abstraction defined by a set of emission factors for each of the criteria pollutants. The resources used in a process can be allocated to one or more technologies and then the entire life cycle is modelled once processes are combined into pathways (ibid).

All the resources and technologies used in the process of a pathway are combined to calculate the energy and emissions associated with each pathway which has a single main product. The energy and emissions of a pathway that are calculated are used as upstream values for the corresponding product in the case of being used as an input to any process within the model. The circular references are resolved through iterative calculations. An input-output model is used for each stage process within the fuel production pathway.

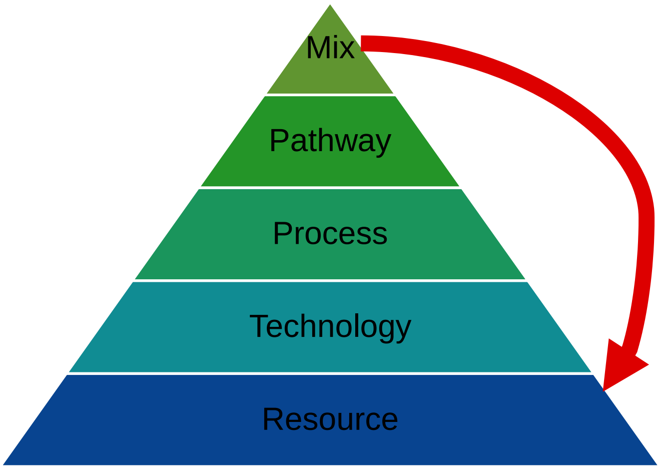

Figure 4 **Flow of calculation in the GREET** (Argonne National Laboratory, 2021)

In GREET, calculation is based upon:

- energy consumption including total energy (energy in non-renewable and renewable sources) and fossil fuels (petroleum, natural gas, and coal),
- water consumption,
- greenhouse gases (GHG) emissions and
- air pollutant emissions including volatile organic compounds, carbon monoxide, nitrogen oxides, particulate matter with different sizes (Argonne National Laboratory, 2021), (Argonne National Laboratory, 2014).

Allocation methods are based on mass, energy content, market prices or resolved via a system expansion and used to assign impacts and benefits to multiple co-products of the same process or from various systems providing multiple functions, e.g., products and waste management.

3.3 Fuel Description

3.3.1 Ethanol

In the U.S., ethanol has accounted for more than 10% of the gasoline market share in 2019 due to blending, during which corn ethanol production has increased from 6.1 billion liters in 2000 to 57 billion liters in 2019 (U. Lee et al., 2021) This is further encouraged by biofuel policies like US Environmental Protection Agency's (EPA's) Renewable Fuel Standard (RFS) and California's Low-Carbon Fuel Standard (LCFS) (ibid).

The system boundaries for ethanol are similar for different feedstocks such as sugarcane, corn stover, miscanthus etc. To provide an idea of the system boundaries, corn-based ethanol is shown in Figure 5, and consists of four major stages, namely farming, ethanol production, ethanol transportation and distribution (T&D), and ethanol combustion.

All the GHG emissions i.e., CO_2, CH_4 and N_2O are accounted for in each stage as well as upstream emissions of inputs to each stage (e.g., electricity, natural gas, fertilizer, etc.). The ethanol combustion stage accounts for ethanol combustion emissions during vehicle operations, the CO_2 emissions from ethanol combustion are offset by uptake of CO_2 during corn plant growth, meaning that biogenic CO_2 emissions from combustion are considered carbon neutral.

Ethanol production has significantly evolved during the past two decades mostly due to increase in both corn farming and biorefineries. Corn yield per hectare has grown continuously while chemical inputs per hectare remain constant leading to a decrease in fertilizer intensities per corn harvest. In addition, increased corn grain ethanol yield and reductions in energy use have reduced the life-cycle greenhouse gas (GHG) emissions per megajoule (MJ) of corn grain ethanol produced and used. In 2014, the carbon intensity of corn ethanol was estimated to be 65.5 gCO_2e/MJ, including LUC GHG emissions of 9.0 gCO_2e/MJ, while the calculated CI of corn ethanol is 53.2 gCO_2e/MJ (including LUC GHG emissions of 7.4 gCO_2e/MJ) in 2020 (U. Lee et al., 2021).

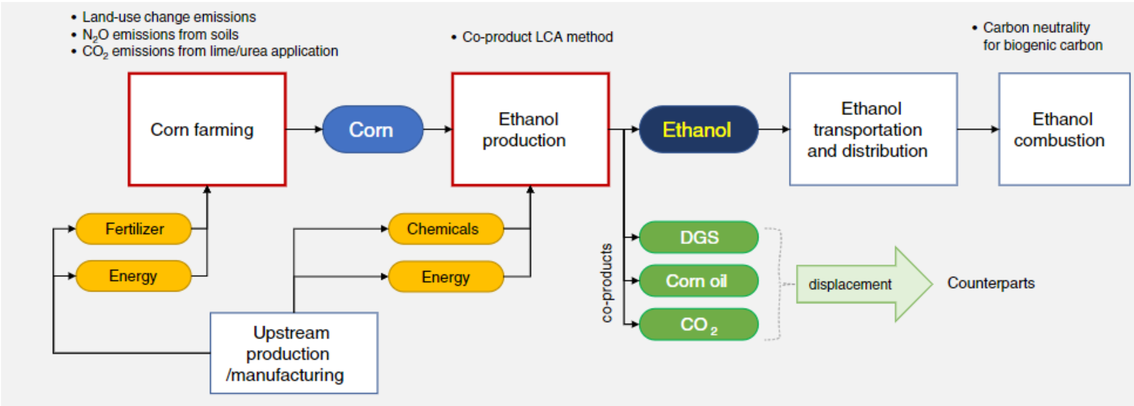

Figure 5 System boundary for Corn ethanol production in the GREET model (adapted) (ibid)

3.3.2 Biodiesel and Renewable Diesel

In the U.S., two major types of biomass-derived diesel are available in the market, including biodiesel (fatty acid methyl ester biodiesel) and hydrogenation-derived renewable diesel (RD). Biodiesel (BD) is produced via the transesterification process, whereas renewable diesel (RD) is produced using the catalytic hydro-processing method.

The system boundary shown in Figure 6 provides information on biodiesel (fatty acid methyl ester) and Renewable diesel (hydro processed esters and fatty acids) pathways produced from vegetable oil from oilseed crops (soybean, rapeseed/canola, carinata (aka Ethiopian mustard)) and low-value feedstocks (inedible beef-tallow, Distillers corn oil (DCO), and used cooking oil (UCO)). For oilseed crops, key stages include biomass production (i.e., farming), oilseed crushing and oil extraction, biofuel conversion, and fuel distribution and consumption. In the case of tallow and UCO pathways, key stages are grease/oil rendering, biofuel conversion, and fuel distribution and consumption. Within all waste-based pathways for BD and RD, the most prominent feedstock, inedible beef tallow which is a recovered by-product from the meat production process does not share upstream emissions (e.g., livestock cultivation).

GHG emission reductions from producing biodiesel and renewable diesel from soybean, canola (rapeseed), and carinata oils range from 40% to 69% including land-use change estimations when compared with petroleum diesel. In comparison, the waste feedstocks such as animal fats, used cooking oil, and distillers corn oil to biodiesel and renewable diesel could achieve greater WTW GHG reductions of 79% to 86% compared to fossil diesel (H. Xu et al., 2022), (B. Riazi, 2020), (R. Chen et al., 2017-2018). The key factors driving biodiesel and renewable diesel lifecycle GHG emissions consist of land-use change, allocation methods influencing the values, fertilizer use, nitrous oxide used in crop farming, energy inputs to grease rendering and the energy and chemical inputs for biofuel conversion (H. Xu et al., 2022).

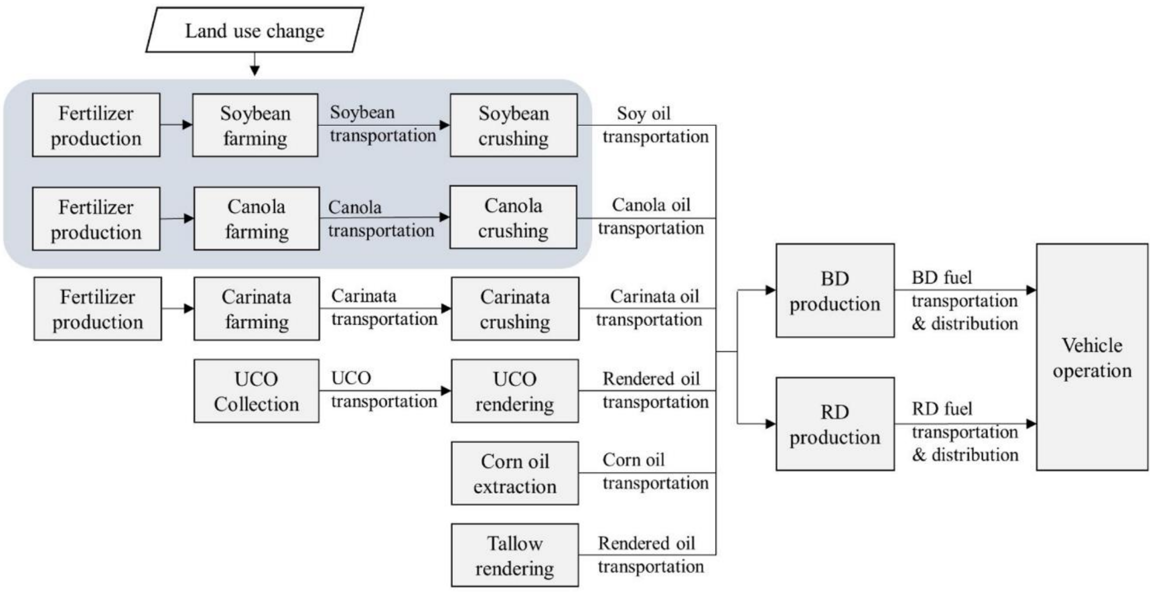

Figure 6 System boundaries for biodiesel and renewable diesel pathway (adapted) (H. Xu et al., 2022)

For oilseed feedstock-based biodiesel, the GHG emissions are lower than for the RD route as the transesterification process is less energy-intensive than hydro-processing. On the other hand, animal waste biodiesel has slightly higher emissions than the RD from animal fats due to higher energy use for pre-treatment (ibid). The process level hybrid allocation method is used for attributing the energy use and emissions to the various products ranging from oilseed crushing, animal fat rendering and biofuel conversion. A mass based allocation is used for both oilseed crushing and animal fat rendering due to oilseed meals and MBM having protein or feed products rather than energy products. An alternative allocation method based on market based allocation was also applied to both oilseed crushing and animal fat rendering to check the sensitivity of results for a different coproduct allocation method. For renewable diesel production, the energy based allocation method was used because co products from hydro processing- fuel gas, LPG, and naphtha are energy based products. For biodiesel production, market based allocation was used as the co product glycerin from the transesterification process is not an energy product.

In the U.S., the production and consumption of biomass-derived diesel have been expanding steadily in the past decade. Biodiesel production has increased from 1.3 billion liters a year to more than 7.1 billion liters in 2020 (ibid), (U.S. Energy Information Administration, 2022) guided primarily by U.S. biofuel policies such as Renewable Fuel Standard and California Low-Carbon Fuel Standard.

3.3.3 Liquified Biomethane (Bio-LNG)

In the US, between 8 and 77 million dry tons of sludge is generated from wastewater treatment plants (WWTP) and municipal solid waste (MSW) (EPA, 2006) (U. Lee et al., 2016). Sludge, which is commonly treated in Anaerobic Digesters (AD), produces biogas that is largely flared to reduce methane emissions. Sludge has a homogeneous characteristic and high energy content and can be used as a potential feedstock for conversion processes to produce renewable natural gas (RNG), which can be further processed to produce compressed biomethane (Bio-CNG) and liquified biomethane (Bio-LNG) (ibid). When compared to gasoline and diesel, the sludge to renewable natural gas via anaerobic digestion leads to WTW GHG emission reduction between 39% to 80%. These reductions are due to GHG credits within the fuel LCA based on avoided GHG emissions under the counterfactual scenario, and/or fertilizer displacement credits(ibid).

As shown in Figure 7, in the system boundaries, the alternative AD case utilizes biogas for energy recovery instead of flaring it as in the counterfactual scenario. There are also other processes (e.g., sludge collection, digestate storage, dewatering, and disposal) included as in the counterfactual scenario. After the first cleanup process, the alternative AD generates heat and power in Combined Heat and Power (CHP) by burning biogas. The heat generated from CHP via a boiler is used to meet the onsite thermal demand, while the electricity from CHP can be used to meet the onsite electricity demand and exported if there is an excess). The rest of the cleaned biogas is further processed (second cleanup) to produce pipeline-quality RNG. RNG is then transmitted to refueling stations via pipeline, compressed, and used as compressed biomethane (Bio-CNG) and liquified biomethane (Bio-LNG) (U. Environmental Protection Agency, 2018), (U. Lee et al., 2016).

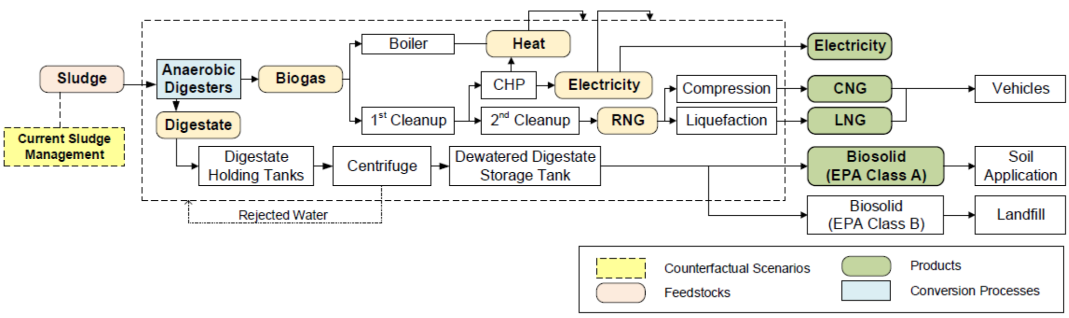

Figure 7 System boundary for wastewater sludge-based Bio-CNG and Bio-LNG via anaerobic digestion (adapted) (U. Lee et al., 2016)

The well-to-wheel values for Bio-LNG produced from MSW or sewage sludge are negative due to avoided landfill emission (mainly CH_4), which has 30 times the global warming potential (GWP) of CO_2, thus resulting in carbon credits for the avoided emissions (U. Lee et al., 2021) In GREET, the carbon intensities of waste derived renewable natural gas is much lower than their European counterparts due to low yields leading to high emission credits (ibid)

4 Comparison of GHG databases

4.1 Comparison with European databases

In comparison to publicly available GHG databases such as JECv5, RED II, UK BEIS and CO2 emissiefactoren; the GREET model has a more comprehensive database and fuel availability, as shown in Table 2. The GREET model has been expanded and regularly updated since 1995. There are other European LCA databases with wide coverage such as ecoinvent, however, it requires a licensed fee to use.

The major difference between the sources is the handling of multifunctional processes, for example when a refinery supplies a wide range of products or when certain biofuel pathways produce energy or animal feed as a by-product. Oil refineries, which are highly complex and integrated systems supplying several assorted products with different properties, require an approach to allocate emissions to multiple products arising from the refining processes (Smart Freight Centre and ifeu, 2021). In JEC v5, which utilizes a consequential approach, a linear programming model of an oil refinery is used to check what changes result from a marginal difference in certain refinery output. Using these results, a division of the refinery emissions is applied between the products resulting in relatively high emissions for products that are in high demand such as diesel or gasoline and lower emissions (or negative emissions) for products like bitumen or heavy fuel oil (ibid). This differs from the approach taken by GREET which primarily uses the attributional LCA approach to assign refinery emissions, where the energy and emissions burdens of individual intermediates are estimated within the refinery by allocating the burdens at the process/unit level using energy allocation by default. These approaches lead to a different balance in emissions across the refinery outputs. In contrast to JEC v5, the RED II follows a mainly attributional approach by allocating the process emissions to products according to the share of the energy content.

The UK BEIS and CO2emissiefactoren website data have a similar approach as their primary function is to provide information in a particular format that is more directly useable by practitioners, whether companies with a need to report emissions or those that support them to do so. UK BEIS provides much greater detail in the background and breakdown of emission factors with a more comprehensive self-contained analysis, whereas the CO2emissiefactoren website generally includes data from well-regarded external sources. Both data sources can be traced back to the JEC WTW v4 study published in 2014.

The attributional approach is generally preferred for GHG accounting since it is based on the typical emissions from the fuels, whereas the consequential approach is more appropriate for use in assessing changes away from the current situation and looking at the effect of substituting current fuels or production processes with alternative technologies and feedstocks.

Table 2 Overview of scope and methodological approach (Adapted and edited from the GHG emission factors for road freight vehicles (Smart Freight Centre and ifeu, 2021)**)**

		GREET	JEC WTW study v5	RED II	CO_2 emissie-factoren	UK BEIS
Scope	Time period validity	2021 and 2035+	2016 and 2025+	2018	2020	2019
	New energy infrastructure construction included		No	No	No	No
	Geographic boundary	USA	Europe	Europe	NL	UK
Fuel Cycle	WTT	Yes	Yes	Yes	Yes	Yes
	Disaggregation of WTT elements	Yes	Yes	Yes, partially	No	No

	TTW	Yes	Yes	Yes, partially	Yes	Yes
Emissions	CO_2	Yes	Yes	No	No	Yes
	CO_2e	Yes	Yes	Yes	Yes	Yes
	CH_4 contribution separated	Yes	Yes	No	No	Yes
	N_2O contribution separated	Yes	Yes	No	No	Yes
Land use	Land Management Changes	Yes	No	No	No	No
	Direct LUC	Yes	No	Yes, partially	No	No
	Indirect LUC	Yes, partially	Yes, partially	Yes, partially	Yes, partially	No
Allocation approach	Attributional	Yes	No	Yes		
	Consequential	Yes, partially	Yes	Yes, energy allocation		Implied
	Mixed	Yes	Yes			
	Approach to biogenic emissions	CO_2 balance	CO_2 balance	CO_2 balance	CO_2 balance	CO_2 balance
	Approach to waste feedstock	emission free	emission free	emission free		emission free
Fuel properties	Density and heating value provided?	Yes, lower and higher heating values	Yes, lower heating value	Yes, lower heating value	No	Yes, lower heating value
Vehicle cycle	Is vehicle life cycle provided	Yes	No	No	No	No

In GREET, emission factor values are subdivided into feedstock, fuel and vehicle operation. In reporting the emission factors from the GREET model, the TTW value consists of traditional greenhouse gases (CO_2, CH_4 and N_2O) and air pollutants such as CO (carbon monoxide) & VOC (volatile organic compound) which are oxidized into CO_2.

The GHG emission factor values from the GREET model, which are subdivided into different emission categories apart from CO_2, are clearly mentioned, whereas for RED II this is not the case. For JECv5, the emissions are split into CO_2, CH_4 and N_2O based on IPCC 2007, however, the exact characterization factors are not stated in the text or excel file. However, to be consistent with guidelines from GHG protocol, the GLEC Framework does not include CO & VOC values, only CH_4 and N_2O values are included. However, CO & VOC values are counted in their fully oxidized form as CO_2 in the GREET model.

Furthermore, when calculating TTW values for biobased fuels, (biogenic) CO_2 is considered zero due to the assumption that CO_2 that is released was previously absorbed by plants and animals[10], [30]. In the case of biomethane from all waste based feedstocks, there is credit for avoiding direct methane emissions given to the output.

On a case-by-case basis, the GHG emissions from feedstock cultivation can be higher for certain biofuels in Europe as compared to North America due to the contribution of land-use change emissions and the productivity and yield capacity of the feedstock. In Europe, a high proportion of the feedstocks is imported whereas the balance appears to favor domestically grown or produced feedstocks in the US.

4.2 Coverage of fuels

In a comparison of all the approaches of the sources for road fuel pathways, Table 3 sets out a summary of the coverage. The coverage of CO2emissiefactoren and UK BEIS reflects fuels that currently exist in the market, whereas RED II focuses on biofuels and the JEC WTW v5 presents a broad set of current and potential future road transport fuels as possible for the EU market, while GREET presents an extensive set of fuel production pathways for the North American market.

Currently, GREET consists of more than 100 production pathways (for fuels and products) from various energy feedstock sources including conventional fossil resources such as petroleum, natural gas, and coal along with renewable fuel pathways from corn, sugarcane, soybeans, cellulosic biomass, waste feedstocks, etc. The JECv5 study also contains many fuel categories such as fossil-derived fuels, biofuels from vegetable oil, ethers, hydrogen, etc. in contrast RED II only contains biofuels. Compared to sources in Europe, GREET is not limited to the HVO (Hydrotreated vegetable oil) process to produce renewable diesel, it also includes other processes such as gasification, pyrolysis and other biochemical and thermochemical technologies.

The only similarity between all these sources is coverage of the conventional biofuels such as HVO, bioethanol and biodiesel that are well enough established in the market.

Table 3 Overview of coverage of fuel types (Adapted and edited from the GHG emission factors for road freight vehicles)

		GREET	JEC v5	RED II	CO_2 emissie-factoren	UK BEIS
Fossil fuels	Diesel	Yes	Yes	Yes[1]	Yes	Yes
	Gasoline	Yes	Yes	No	Yes	Yes
	LNG	Yes	Yes	No	Yes	Yes
	LPG	Yes	No	No	No	Yes
	CNG	Yes	Yes	No	Yes	Yes
	Dimethyl ether	Yes	Yes	No	No	No
	Hydrogen (from methane)	Yes	Yes	No	Yes	No
Biofuels	Biodiesel	Yes	Yes	Yes	Yes	Yes
	Renewable Diesel via another process[2]	Yes	No	Yes	No	No
	HVO	Yes	Yes	Yes	Yes	Yes
	Liquified Biomethane (LBM) Bio-LNG	Yes	Yes	No	No	No
	Compressed Biomethane (CBM) /Bio-CNG	Yes	Yes	Yes	Yes	No
	Bio methanol	Yes	Yes	Yes	No	Yes
	Bioethanol	Yes	Yes	Yes	Yes	Yes
	Biohydrogen[3]	Yes	Yes	No	No	No
Synthetic[4] and e-fuels	Synthetic diesel	Yes	Yes	No	No	No
	Synthetic methanol	No	Yes	No	No	No
	Synthetic LNG	No	Yes	No	No	No
	Synthetic CNG	No	Yes	No	No	No
	eDiesel	Yes	Yes	No	No	No
	eMethanol	Yes	Yes	No	No	No
	eEthanol	Yes	No	No	No	No
	eLNG	No	Yes	No	No	No
	eCNG	No	Yes	No	No	No
	eHydrogen	No	Yes	No	Yes	No

4.3 Compatibility with the GLEC approach

Although the GREET and the GLEC Framework have many similarities in accounting principles, which are highly compatible, there are slight methodological differences. There are some inconsistencies in the GHG accounting rules among the emission factor developers, regulatory operators such as Low Carbon Fuel Standard used by GREET model and Renewable Energy

[1] RED II provides a fossil comparator at 94g CO_{2e}/MJ (WTW), irrespective of the type of fossil fuel

[2] via gasification, pyrolysis, and other biochemical and thermochemical technologies

[3] Includes liquid and gaseous forms of H_2

[4] Gas-to-liquid

Directive used in Europe, and standard developers (e.g. GHG protocol used by the GLEC Framework). This creates uncertainty in the market for fuel suppliers and end-users intending to use low-emission fuels e.g., biofuels. This leads to an aggravated issue when a certain corporation's transport operation spans different regulatory boundaries such as Europe and the US.

An example could be the Low Carbon Fuel Standard, intending to incentivize the fuel market in California, which includes avoided emissions to the carbon intensity for biofuels reported in the GREET model, whereas the GHG Protocol does not, as reported in the GLEC Framework. Instead, the GHG Protocol, which sets the standard for corporate emission accounting, recommends that avoided emissions are not to be added into the Scope 3 when calculating the final WTT values. End-users accounting GHG emissions are confused by these different approaches and how to account for these principles in their reporting structure.

Therefore, it is required to modify the GREET emission values for example for renewable natural gas due to credits for avoided emissions as it leads to negative value which is not in line with the attributional approach followed by the GLEC Framework and ISO 14083. Thus, the report currently shows the emission factors of fuels as represented in the GREET model for the time being, however, to be included in and aligned better with the GLEC Framework, these values need to be modified. Thus a common consensus is required for the freight sector with a special focus on harmonizing emission factors across Europe and the US, and expanding further to accommodate a global emission database in the near future.

Other challenges faced by fuel suppliers in the GLEC Framework revolve around dealing with biogenic and industrial removals, credit schemes, and the inclusion of iLUC. iLUC values are provided separately if necessary and are not included in well-to-wheel values as the methodology to estimate iLUC is still relatively new and more uncertain than other aspects of the emission factors. Due to the uncertainty, none of the sources directly include the impacts of land-use change; however, GREET, RED II and JECv5 do include a possible range of iLUC impacts from certain crop-based biofuels (e.g., corn, palm oil, sugarcane, rapeseed, soybean).

5 Results

The objective of this report to publish well-founded information about the life cycle GHG emissions of potential low emission transition fuels for road freight in the US has been achieved through outlining an overview of the GHG emission factors from the GREET model. The report has identified similarities and differences between GREET and European databases such as JECv5 and RED II, based on their calculation approach and accounting rules. Emission factors for the same fuel can vary a lot depending on the database. This will form a base for the upcoming GLEC update and already helped in the development of the US emission factors in ISO 14083 (forthcoming).

Fuel emission factors depend on the region of operation due to different feedstock mixes and region-specific processes or energy provision emissions (e.g., electricity used). iLUC is relevant and in some cases, a significant contributor to the overall greenhouse gas emissions of biofuel and is, therefore, important to consider. In GREET, CCLUB is used to identify iLUC values for different feedstocks, which are available on the Argonne National Laboratory website. In the EU, the RED II directive has provided iLUC values. As an end-user calculating the emission factors of fuels, iLUC values can be added using the respective databases.

However, due to high uncertainties in the exact values of iLUC emissions, SFC in the GLEC Framework currently do not include iLUC into the calculation of emission factors. In the near future, it is anticipated that iLUC values will be more widely available and reliant and therefore consolidated data on iLUC will be incorporated in the freight emission reporting.

The results of this report can be further subdivided into two parts. One part identifies the structural differences between, and similarities among GREET, JECv5 and RED II, the other part shows the outcome of the comparison of the emission factor values between the US and Europe.

5.1 Comparison of the structure

The report has identified various differences and similarities among the GREET model, JECv5 and RED II models. Table 4 provides the comparison of the emission factors of the fuel types for road freight in both Europe and North America:

Table 4 Comparison of the GHG emission factors for road freight

	GREET			JEC v5			RED II[5]		
	g CO_2e/MJ								
SI engine	WTT[6]	TTW[7]	WTW[8]	WTT	TTW	WTW	WTT	TTW	WTW
Gasoline	17.1	73.0	90.2	17.0	73.4	90.4	NA[9]	NA	NA
Ethanol-Corn Stover	12.6	0.3	12.9	NA	NA	NA	NA	NA	NA
Ethanol- Sugarcane	25.9	0.3	26.3	23.5	0	23.5	28.1	0	28.1
Ethanol- Corn	55.3	0.3	55.6	57.3	0	57.3	48.5	0	48.5
Ethanol-Miscanthus	-1.3	0.3	-1.0[10]	NA	NA	NA	NA	NA	NA
Ethanol-Switchgrass	16.5	0.3	16.8	NA	NA	NA	NA	NA	NA
CI engine									
Diesel	15.5	75.0	90.5	18.9	73.2	92.1	NA	NA	NA
Biodiesel-Soybean	16.5	4.1[11]	20.6	55.8	0	55.8	42.2	0	42.2
Biodiesel-Rapeseed	25.9	4.1	30.0	48.4	0	48.4	45.5	0	45.5
Biodiesel-Corn oil	5.8	4.1	9.9	NA	NA	NA	NA	NA	NA
Biodiesel-Waste Cooking Oil	7.6	4.1	11.7	8.3	0	8.3	11.2	0	11.2
Biodiesel-Algae	44.8	4.1	48.9	NA	NA	NA	NA	NA	NA
Biodiesel-Tallow	14.8	3.9	18.7	13.8	0	13.8	15.3	0	15.3
Renewable Diesel-Tallow	17.7	0.1[12]	17.7	16	0	16	16	0	16
Renewable Diesel-Soybean	23.4	0.1	23.4	60.2	0	60.2	41.9	0	41.9
Renewable Diesel-Rapeseed	33.0	0.1	33.1	51.9	0	51.9	45.8	0	45.8
LNG	19.1	57.6	76.7	16.6	55.1	71.7	NA	NA	NA
Bio-LNG Landfill gas	73.8	1.1	74.9	NA	NA	NA	NA	NA	NA
Bio-LNG- Maize	NA	NA	NA	30.6	7.9	30.6	50.5	7.9	58.4

[5] RED II values are typical values
[6] Well-to-tank
[7] Tank-to-wheel
[8] Well-to-wheel
[9] Not available
[10] Due to Miscanthus being a dedicated energy crop with high biomass carbon and SOC sequestration (roots)[31], [32]
[11] 4.02 gCO_{2e}/MJ is a constant combustion value due to the burning of fossil methanol included in all types of biodiesels
[12] Rounded off from 0.05 to 0.1

Bio-LNG- Wet manure	-104.1[13]	1.1	-103.0	-30.1	7.9	-22.2	-31.4	7.9	-23.5

- GREET has very extensive alternative fuel production pathways and covers more fuel types than RED II or JEC v5. However, the possibilities to include all fuel pathways in this report are limited due to availability of feedstock and products in each particular regional market for low emission fuels used in road freight.
- Breakdown of tailpipe emissions in the GREET model are separately mentioned and divided into the three traditional greenhouse gases (CO_2, CH_4, and N_2O) and the air pollutant emissions from transportation fuels. Volatile organic compounds (VOC) and carbon monoxide (CO) are counted in their fully oxidized forms as CO_2. Whereas, in the case of JECv5 and RED II, they are not separately reported.
- Based on a case by case comparison, emission factor values for feedstock cultivation are higher for Europe as most of the feedstock is imported, whereas in North America due to high productivity and yield for domestically produced feedstock, the contribution of feedstock cultivation to the emission factor is lower.
- When considering renewable diesel, GREET is not limited to HVO (Hydrotreated vegetable oil) as it also considers other alternative processes based on gasification, pyrolysis and other biochemical and thermochemical technologies.
- For the reporting and calculation of iLUC values, GREET includes more consistent and robust values than RED II and JECv5 based on the calculation approach described in the CCLUB and GTAP-Bio model. However, since there is no consistent way of calculating iLUC across different geographies and associated with different crop-based feedstocks, iLUC is therefore presently not included in the calculation of emission factors in the GLEC Framework.
- The corn stover industry which collects, processes and transfers corn stover to biofuel industries do not need additional land to provide feedstocks but pays higher fertilizer costs to maintain productivity of land. Corn stover has little impact on LUC, however, biofuel produced from corn stover does not need land, it affects the land prices and marginally causes some reforestation based on general equilibrium model. In the real world, corn stover biofuel production may produce some changes in corn-soy rotation in the short run (F. Taheripour and W. E. Tyner, 2013).
- Ethanol produced from miscanthus and switchgrass has negative LUC due to net carbon sequestration, as both crops are dedicated energy crops with high biomass carbon and soil organic carbon (SOC) sequestration (roots) (ibid), (X. Zhao et al., 2021).
- Biofuels produced from waste streams such as used cooking oil, do not carry iLUC emissions since their use does not impact land use. It is therefore important to consider what the indirect emissions associated with a feedstock are when assessing the emissions performance of various sources of biofuel. Currently, only values of iLUC for soybean and rapeseed-based biodiesel for the North American region can be found in the CCLUB model.

From the initial comparison, it can be concluded that GREET values have some minor differences from their counterparts in Europe. These minor differences need to be acknowledged and adjusted to be incorporated in the GLEC Framework and ISO 14083. For example, the biogas values are not included in the ISO 14083, due to the credits for avoided emissions leading to negative values as it is not in line with the attributional approach followed by ISO 14083 and the GLEC Framework.

5.2 Comparison of emission factors

The following figures show results for comparison of emission factors (composed of WTT, TTW and WTW) for GREET, JECv5 and RED II typical values.

[13] Carbon credits from avoided emissions

In Figure 8, in comparison to fossil gasoline, the WTW GHG reduction of bioethanol from sugarcane is 65%. However, there is a small fraction of methane and N_2O is present in the TTW values of ethanol produced from sugarcane and corn in the GREET model. Comparing different GHG databases, ethanol produced from sugarcane has almost similar emission values. However, for ethanol produced from corn, the emission values differ due to differences in procurement of feedstocks as corn is domestically produced in the USA, while it is mainly imported into Europe.

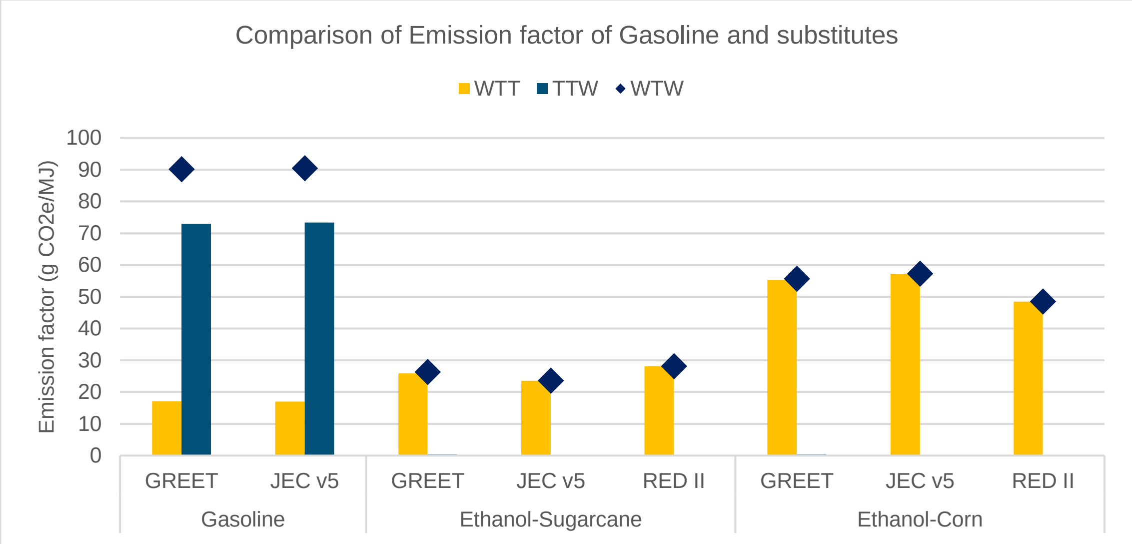

Figure 8 Overview of emission factors for ethanol and substitutes

In Figure 9, comparing the WTW value of biodiesel from soybean, the value from GREET is at least 50% lower than the value from JECv5. The most likely reason for this is the production of soybean domestically in the US, whereas in Europe it is mainly imported. For 100% biodiesel blends in the GREET, the emission values include fossil methanol which acts as a denaturant has an emission value of 4.02g CO_{2e}/MJ.

Biodiesel values have lower WTW emissions than renewable diesel due to the energy required for producing renewable diesel being much higher. The renewable diesel values in the GREET model are taken from the ASPEN+ model which is a leading chemical process simulator in the market. Only first and second-generation feedstocks for biodiesel and renewable diesel can be seen (for 3rd generation feedstock values refer to the GREET1 model).

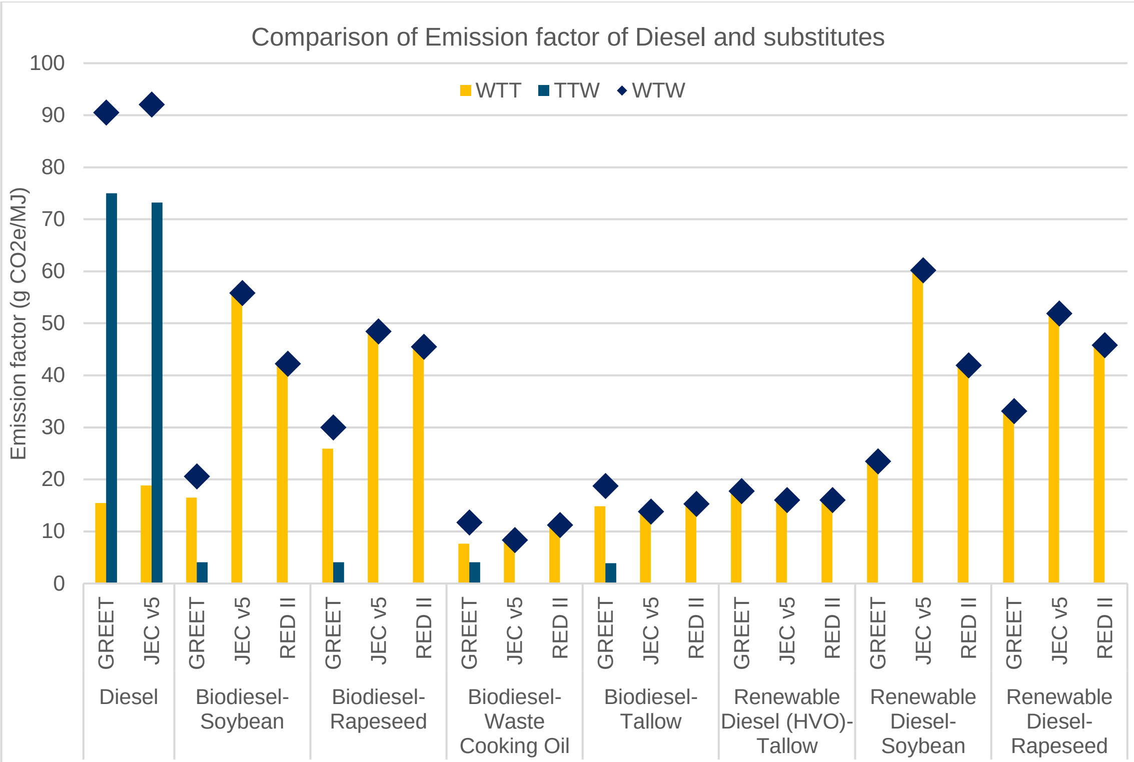

Figure 9 Overview of emission factor for diesel and substitutes

Emission factors are generally shown on the basis of each fuel (energy carrier). In Figure 10, however, methane-based fuels present a difficulty in that as the overall emissions depends on the extent of methane slip, which itself depends on the effectiveness of the engine in preventing this leakage of methane, a powerful greenhouse gas in its own right, to the atmosphere. . In GREET, the carbon intensities of waste derived renewable natural gas is much lower than their European counterparts leading to high emission credits and negative emission factors. In comparison, the Bio-LNG value from waste stream for GREET is at least 78% lower than the JEC v5 value mainly due to carbon credits.

Bio-LNG values vary significantly due to the difference in emissions linked to each feedstock and process combination. Credits for the avoided emission of CH_4 make a significant contribution for some options.

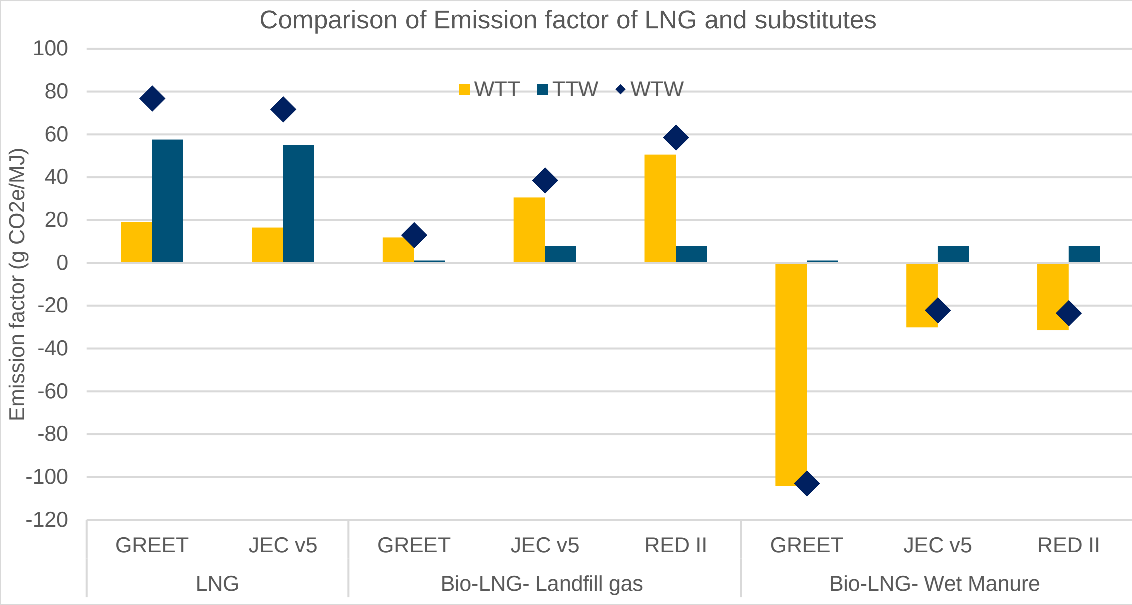

Figure 10 Overview of emission factors for LNG and substitutes

It can be concluded that there are many similarities in RED II, JECv5 and GREET model, with three differences in accounting: (i) accounting of methane slip, (ii)accounting of iLUC, and (iii) accounting of avoided emissions. The JECv5 follows consequetional approach as compared to RED II attributional approach, GREET follows a hybrid approach where both attribuitional and consequetional are used. There is a further variation in completeness of different feedstocks/fuel pathways which can be explained from different availability and pathways. Thus, there is a particular need for harmonization of approaches for emission factors between the US and Europe with development of principles when developing emission factors for GHG emission reporting, in particular for emission factors that are evolving over time.

It is recommended that the methane slip should be included in the emission factors moving forward (as it is currently included in the GLEC Framework). iLUC should be reported seperately considering the current Land Sector Removals Guidance, until there is a reliable and consistent way to estimate iLUC values.

6 Future work

This report has highlighted the major differences between and similarities among the fuel emission factors commonly used in Europe and the US. However, it is recommended to consider the following at later stages to provide a better understanding of the calculation of emission factors for low emission fuels.

- Address the (i) inclusion of methane slip, and (ii) avoided emissions in GHG accounting principles for the end-users to have a universal accounting and reporting structure.
- Develop principles to take into account when developing emission factors for GHG emission reporting, in particular as emission factors are evolving over time due to the introduction of new energy carriers, the available technology for the production of fuels improves, and lower emission energy sources are deployed to power production processes.
- Review how iLUC emissions can be estimated with greater reliability, such that it can be included in freight emissions reporting and the GLEC Framework emission factors.

Future work will include reviewing the availability of synthetic and e-fuels in the market, their respective emission factors and their importance to be included in the GLEC Framework.

7 References

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